The BTeV Experiment

- Physics motivation
  - CP Violation
  - Physics Beyond the Standard Model
- Detector description
- Comparisons to current and future experiments
- R&D Status and current approval status

Physics Motivation

$\Rightarrow$ Make Physics Discoveries!

New Particles

New Symmetries

New Interactions

Energy Frontier

Enough energy to create new particles like Higgs, SUSY, 4th gen. quarks, quark substructure

Search for new symmetries like lepton-quark, SUSY or look for symmetry violations

Look at couplings of high mass particles for evidence of new interactions and new scales

Precision Frontier

New particles can contribute To rare or "forbidden" decays, e.g. kaon decays or in large Charm mixing

Search for symmetry violations e.g. in CP and CPT, or test Symmetries between leptons, e.g. in muon g-2

Look for deviations from theory in couplings of lower mass particles, including e.g. mixing in neutrinos

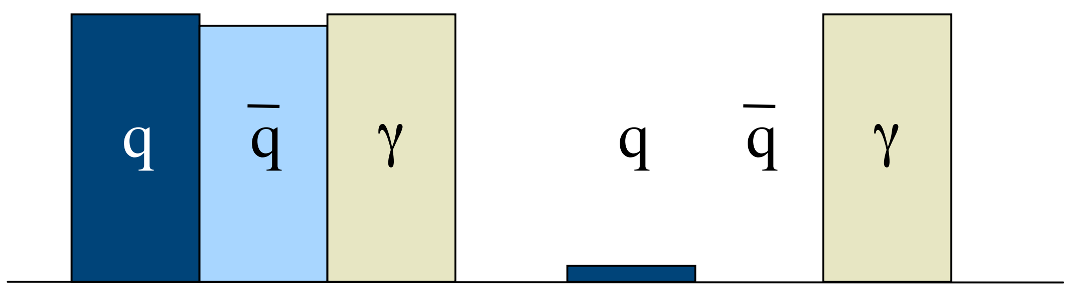
CP Violation: A Fertile Frontier

How did we become a matter (dominated) universe?

Andrei Sakharov's conditions (1967):

- Baryon number violation
- C and CP violation
- Non-equilibrium (or CPT violation)

?



Early Universe

Now

Standard Model

$$(n_q - n_{\bar{q}})/n_q \sim (n_q - n_{\bar{q}})/n_\gamma \sim \quad n_B/n_\gamma \sim 10^{-9} \xleftarrow{?}$$

CPV: A New Physics Frontier

Matter/anti-matter asymmetry: SM Electroweak Baryogenesis

- Baryon number violation - non-perturb. EW at high T
- C and CP violation - in quarks
- Non-equilibrium - EW phase transition (bubbles)

Get $n_B/n_\gamma \sim 10^{-20}$ $\longrightarrow$ New Physics beyond SM(!)

Where to look!

- Additional sources of CP violation:
  - in the quark sector
  - two-doublet Higgs models
  - SUSY (MSSM)
  - …..

CPV: A Precision Frontier

CP Violation in quarks and the CKM:

- Relate mass and decay eigenstates/coupling between quarks using the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{array}{cc} & \begin{array}{ccc} \mathbf{d} & \mathbf{s} & \mathbf{b} \end{array} \\ \begin{array}{c} \mathbf{u} \\ \mathbf{c} \\ \mathbf{t} \end{array} & \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta\left(1-\frac{1}{2}\lambda^2\right)\right) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2\left(1+i\eta\lambda^2\right) \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

$\lambda \approx 0.22$

- SM is very predictive - good place to look for "New Physics"!
  All CP violation in quark decays related to a single parameter (η)!

Aside: CP Violation Basics

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

E.g. charged B decays: $B^{\pm} \to f^{\pm}$ reached via 2 weak processes

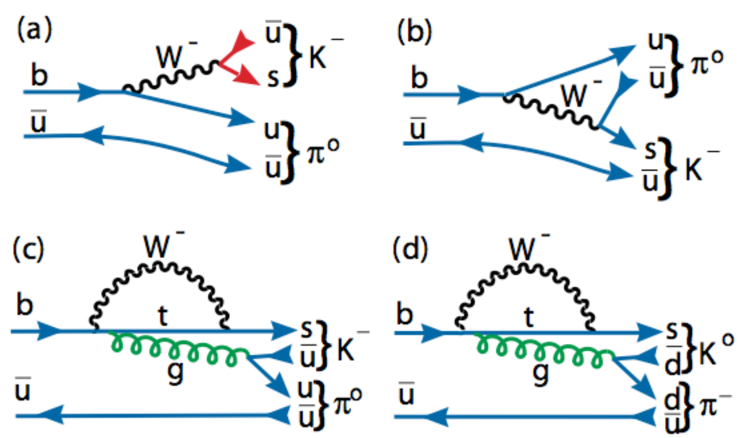
$$A = a_s e^{i\theta_s} a_w e^{i\theta_w} \qquad B = b_s e^{i\delta_s} b_w e^{i\delta_w}$$

$$\bar{A} = a_s e^{i\theta_s} a_w e^{-i\theta_w} \qquad \bar{B} = b_s e^{i\delta_s} b_w e^{-i\delta_w}$$

$$\Gamma - \bar{\Gamma} = |A+B|^2 - |\bar{A}+\bar{B}|^2 = 2a_s a_w b_s b_w \sin(\delta_s - \theta_s)\sin(\delta_w - \theta_w)$$

E.g. $B^- \to K^- \pi^0$

Weak phase difference



Direct CP Violation

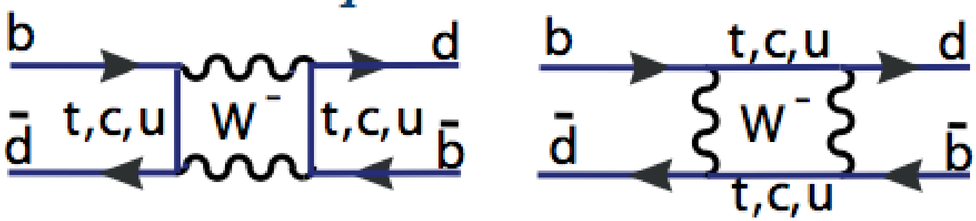
Aside: CP Violation in Neutral B

B^0 and $\overline{\mathrm{B}}^0$ mix: $|B_L\rangle = p|B^0\rangle + q|\overline{B^0}\rangle \quad |B_H\rangle = p|B^0\rangle - q|\overline{B^0}\rangle$

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B^0}\rangle$$

$$|\overline{B^0}(t)\rangle = \frac{p}{q}g_-(t)|B^0\rangle + g_+(t)|\overline{B^0}\rangle$$

CP is violated if |q/p| $\neq$ 1



E.g. $B^0 \rightarrow X\ell^-\bar{\nu}$

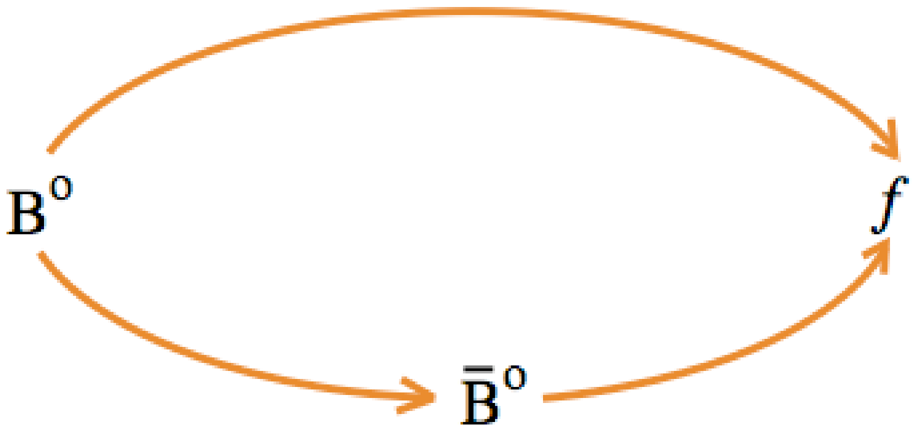
not $B^0 \rightarrow X\ell^+\nu$

$$a_{sl} = \frac{\Gamma(\overline{B^0}(t) \rightarrow X\ell^+\nu) - \Gamma(B^0(t) \rightarrow X\ell^-\bar{\nu})}{\Gamma(\overline{B^0}(t) \rightarrow X\ell^+\nu) + \Gamma(B^0(t) \rightarrow X\ell^-\bar{\nu})} = \frac{1 - \left|\frac{q}{p}\right|^4}{1 + \left|\frac{q}{p}\right|^4}$$

Indirect CP violation

Aside: CP Violation in Neutral B

CP violation via interference of mixing and decays



$$A = \langle f_{CP} | H | B^0 \rangle$$

$$\bar{A} = \langle f_{CP} | H | \overline{B^0} \rangle$$

$$\left| \frac{\bar{A}}{A} \right| \neq 1$$ Direct CP violation

CP violated if $\frac{q}{p} \cdot \frac{\bar{A}}{A} \neq 1$ even if $\left| \frac{q}{p} \right| = 1$ and $\left| \frac{\bar{A}}{A} \right| = 1$

E.g. a non-zero phase

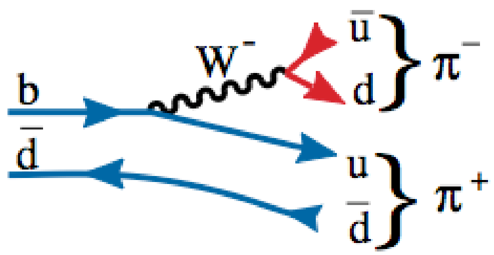
Aside: CP Violation in Neutral B

CP violation via interference of mixing and decays

$$a_{f_{CP}} = \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B^0}(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B^0}(t) \to f_{CP})}$$

$$a_{f_{CP}} = -\mathrm{Im}\left(\frac{q}{p}\cdot\frac{\overline{A}}{A}\right)\sin(\Delta m t) \qquad \left|\frac{q}{p}\right| = 1 \quad \text{and} \quad \left|\frac{q}{p}\cdot\frac{\overline{A}}{A}\right| = 1$$

From mixing



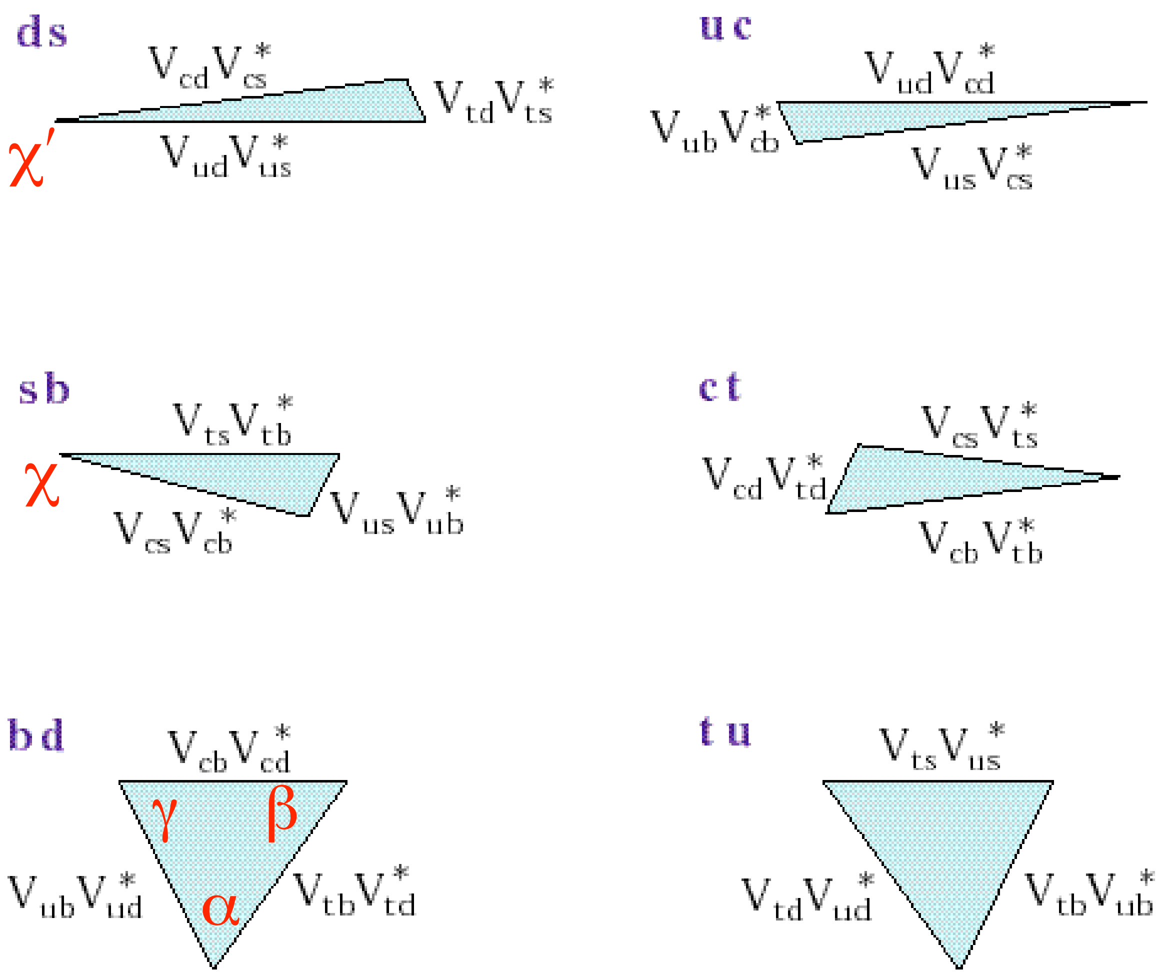
$$\frac{q}{p} = \frac{(V_{tb}^* V_{td})^2}{|V_{tb}V_{td}|^2} = e^{-2i\beta}$$

E.g. $B \to \pi\pi$

$$\frac{\overline{A}}{A} = \frac{(V_{ud}^* V_{ub})^2}{|V_{ud}V_{ub}|^2} = e^{-2i\gamma} \qquad -\mathrm{Im}\left(\frac{q}{p}\cdot\frac{\overline{A}}{A}\right) = -\mathrm{Im}\left(e^{-2i\beta}e^{-2i\gamma}\right) = \sin(2\alpha)$$

(but Penguin contributions)

Aside: Unitarity and CKM Triangles



$$\left|\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\right|^2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Aside: The **bd** CKM Triangle

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$$

Approximate $|V_{ud}^*| \approx 1$ and $|V_{tb}| \approx 1$ gives

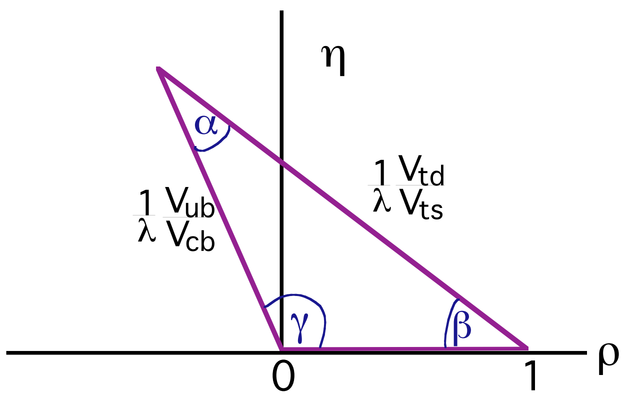
$$V_{ub} + V_{td}^* + V_{cb}V_{cd}^* = 0$$

Approximate $V_{cb}V_{cd}^* = A\lambda^2 \times \lambda$ gives a triangle with sides:

$$1$$

$$\left|\frac{V_{td}}{A\lambda^3}\right| = \sqrt{(\rho-1)^2+\eta^2} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

$$\left|\frac{V_{ub}}{A\lambda^3}\right| = \sqrt{\rho^2+\eta^2} = \frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$



$$\begin{array}{c c} & \begin{array}{ccc} \mathbf{d} & \mathbf{s} & \mathbf{b} \end{array} \\ \begin{array}{c} \mathbf{u} \\ \mathbf{c} \\ \mathbf{t} \end{array} & \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta\left(1-\frac{1}{2}\lambda^2\right)\right) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2\left(1+i\eta\lambda^2\right) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array}$$

Beware conventions/approximations!

Aside: CKM Phases and CP Violation

- The CKM matrix can be expressed with 4 phases:

$$\beta = \arg\left(-\frac{V_{tb}V_{td}^*}{V_{cb}V_{cd}^*}\right) \qquad \gamma = \arg\left(-\frac{V_{ub}^*V_{ud}}{V_{cb}^*V_{cd}}\right)$$

$$\chi = \arg\left(-\frac{V_{cs}^*V_{cb}}{V_{ts}^*V_{tb}}\right) \qquad \chi' = \arg\left(-\frac{V_{ud}^*V_{us}}{V_{cd}^*V_{cs}}\right)$$

- $\alpha = \pi - (\beta + \gamma)$ is not independent in the SM
- Expect α, β and γ large, χ small ~ 1°, and χ' even smaller
- A critical test is: but need lots of data

$$\sin(\chi) = \lambda^2 \frac{\sin(\beta)\sin(\gamma)}{\sin(\beta+\gamma)}$$

Silva and Wolfenstein hep-ph/9610208; Aleksan, Kayser and London hep-ph/9403341

CPV: A Precision Frontier

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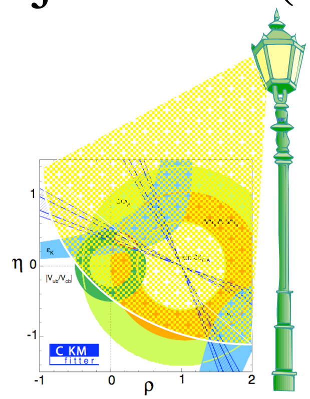
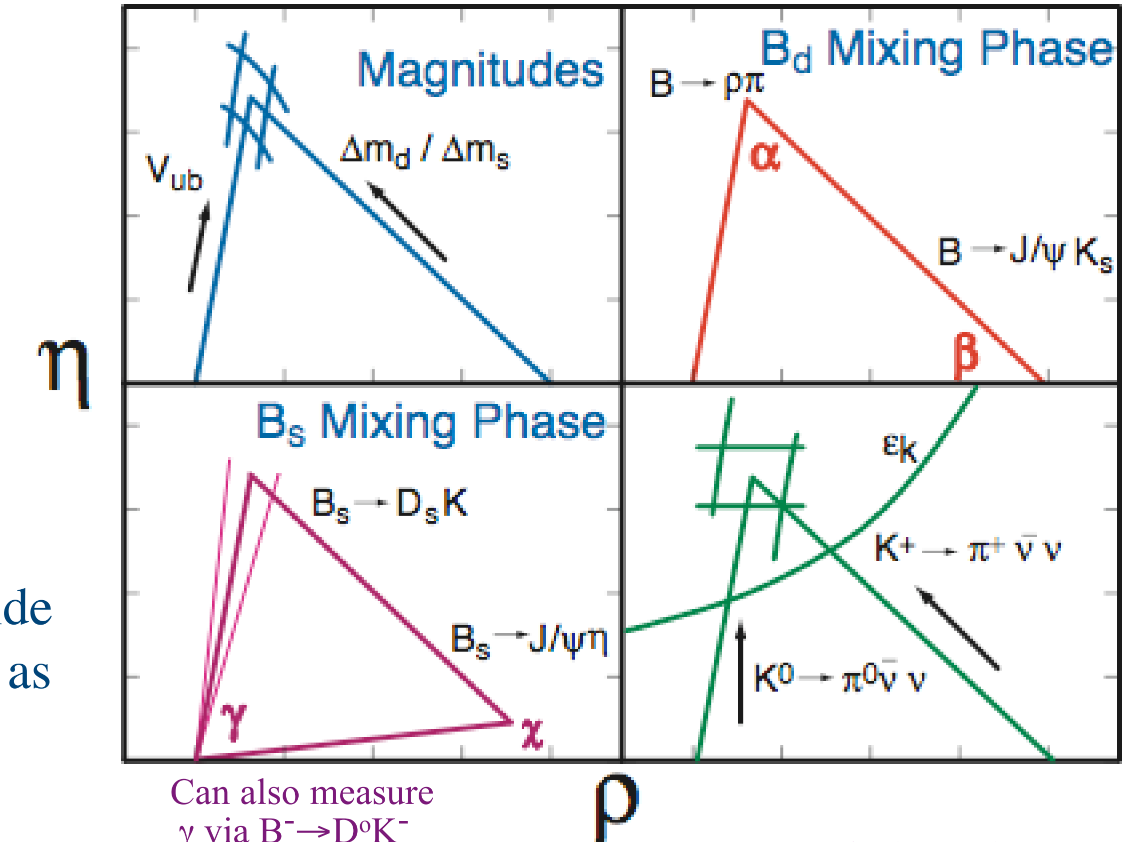
- SM is very predictive - good place to look for "New Physics"!
  All CP violation in quark decays related to a single parameter (η)!

Measurements of the CKM Matrix

Don't just look (measure) under one lamp post!





- Measurements of just the 3 angles are not enough, new physics can hide
- Ambiguities exists as one measures typically $\sin(2\vartheta)$

Can also measure γ via $B^- \to D^o K^-$

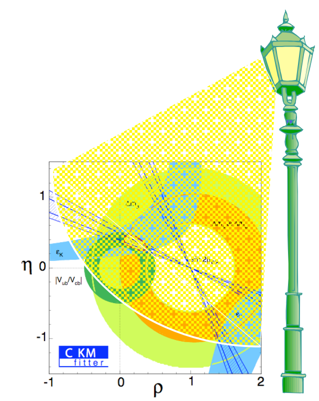
From Peskin hep-ph/0002041

CPV: A Precision Frontier

- The Standard Model CKM matrix is very predictive

e.g. all quark CP-violation is described by η (i.e. 1 parameter)

- To discover new physics (or help interpret new physics discovered elsewhere) we need a comprehensive study of quark flavour physics
  - Need to measure "α", β, γ, χ in many modes/decays
  - Look at rare b decays and mixing
  - Look at CP-violation and rare decays in charm
  - Check flavour independence with kaon decays



- Compare to the comprehensive tests of EW at LEP and SLD - repeat for quark flavour physics!

So don't just look under one lamp post!

B_S Decays: The New Frontier

Will not list 1001 B decay modes with nitty-gritty details instead focus on one item: B_s decays

- The "other Gold-plated" mode: $B_s \rightarrow D_s K$
  theoretically clean way to measure γ (really γ - $2\chi + \chi'$)
  - $B^0 \rightarrow D^{(*)}\pi$ measures $\sin(2\beta + \gamma)$ & large statistics
  - B_d, $B^\pm \rightarrow K\pi$ need Penguin/Tree ratio
  - $B_d \rightarrow DK$, more strong phases & difficult ID
- Measure $\sin(2\chi)$ using $B_s \rightarrow J/\psi\eta^{(\prime)}$ (and $J/\psi\phi$)
  - Silva and Wolfstein:
    Critical test:

$$\sin(\chi) = \lambda^2 \frac{\sin(\beta)\sin(\gamma)}{\sin(\beta+\gamma)}$$

B_S Decays: The New Frontier

- Possible "New Physics" in B_s - $\bar{B}_s$ mixing:
  - "New Physics" compete in loops not in trees
  - "NP" in Δm_s or a CP violating mixing phase
- "New Physics" in $\Delta\Gamma(B_s)$ Lifetime Difference (B_H, B_L)
  - SM value ~ 10-15% is measurable
  - Reduced with "New Physics" ~ $\Delta\Gamma_{CP} \cos(\phi_s)$
    So even limits can exclude (PS of) models of "NP"
  - Large $\Delta\Gamma(B_s)$ allows indep. measurements of some CKM phases using untagged angular distributions

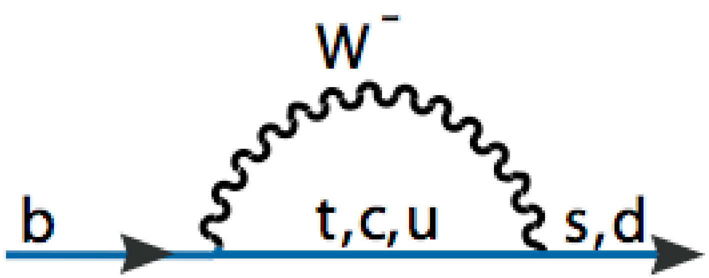
Physics Beyond the SM

Besides CP violation, other mysteries point to physics beyond the SM: e.g. SM "fundamental parameters"

So we expect "New Physics"

Look for "New Physics" by:

- Deviations from SM values, e.g. rare processes

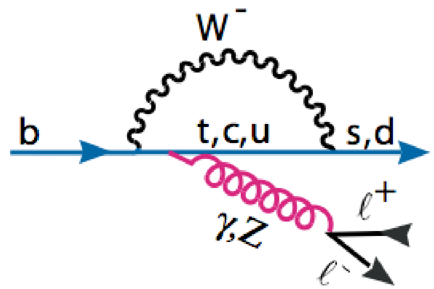


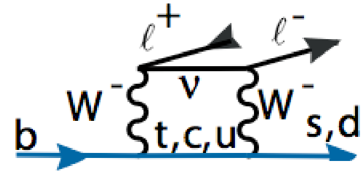
"New Physics" processes can compete with SM loop processes, like FCNC

$b \rightarrow sX$

Rare decay example: $B \rightarrow K^*\mu^+\mu^-$

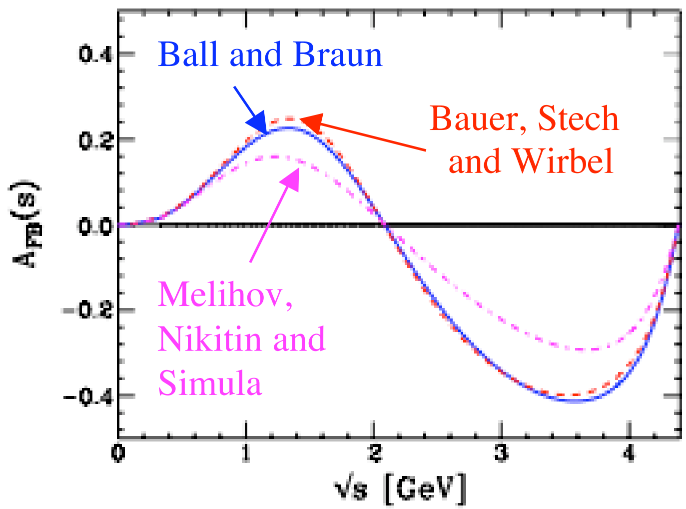
Look at FB asymmetry as a function of the dimuon mass

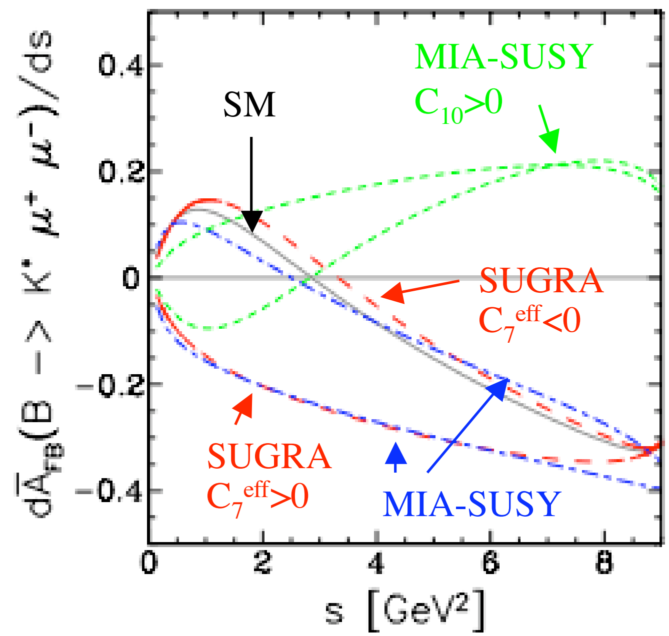




Compare SM and SUSY/SUGRA

SM: Burdman hep-ph/0112063



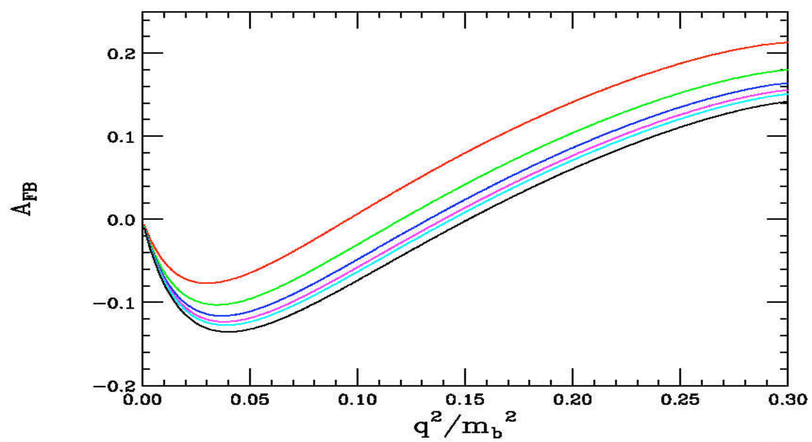


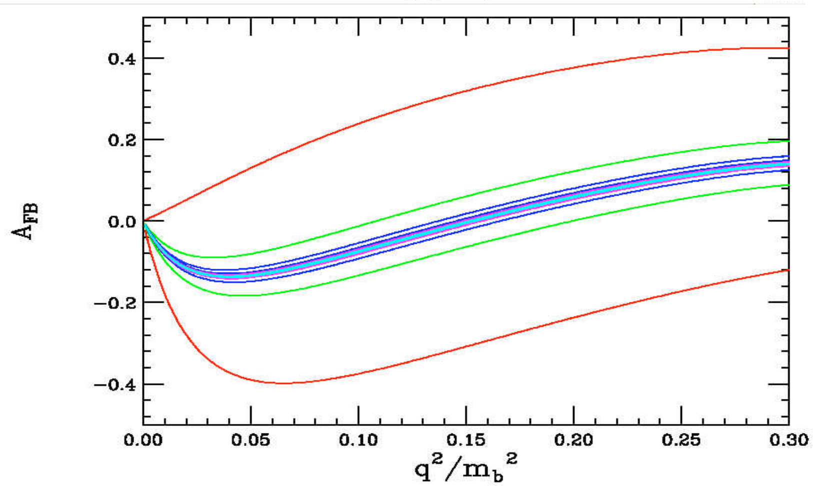
See also Beneka, Feldmann and Seidel hep-ph/0106067

Ali et al. hep-ph/9910221

Rare decay example: $B \rightarrow K^* \mu^+ \mu^-$

Look at FB asymmetry as a function of the dimuon mass





Taken from Hewett WIN03:

Graviton Penguins in $B \rightarrow X_s ll$

T.Rizzo, WG4 talk at 2nd Workshop on B-factory at 10^{36}, SLAC, Oct., 2003

Randall-Sundrum Model
M_1 = 600 – 1000 TeV

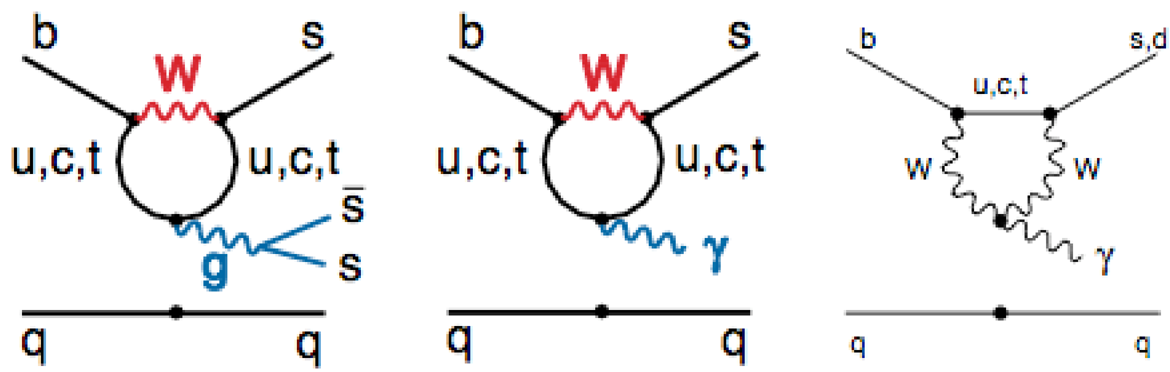
Large Extra Dimensions
M_D = 1 – 2.5 TeV

Probes the TeV scale!

Physics Beyond the SM

Look for "New Physics" by:

- Inconsistencies in SM comparisons
  but must satisfy current constraints: e.g.
  the physics that produces $\sin(2\beta)_{J/\psi Ks} \neq \sin(2\beta)_{\phi Ks}$
  would also affect the $b \to s\gamma$ rate in many models



$\rightarrow$ Correlations

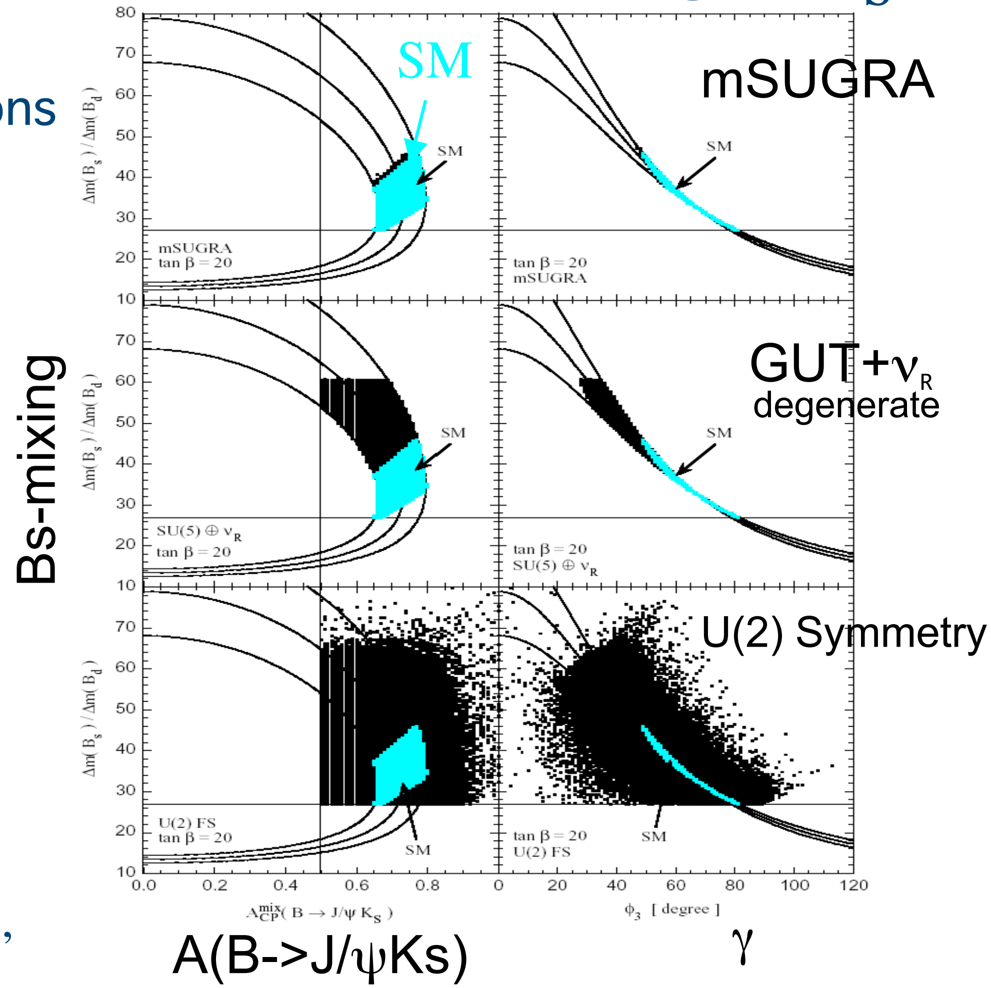
Physics Beyond the SM: E.g. B_s

From Hewett WIN03
Unitarity Triangle Correlations

1. Minimal SUGRA: deviation from the SM is less than 10%.

2. SUSY GUT with ν_R : degenerate-case B_s-mixing can be different from the SM. B-unitarity triangle is closed.

3. U(2) flavor symmetry: Large SUSY corr. to K, B_d, and B_s mixings. B-unitarity triangle may not be closed.



Original plot from Goto et al., hep-ph/0204081

Physics Beyond the SM: LHC?

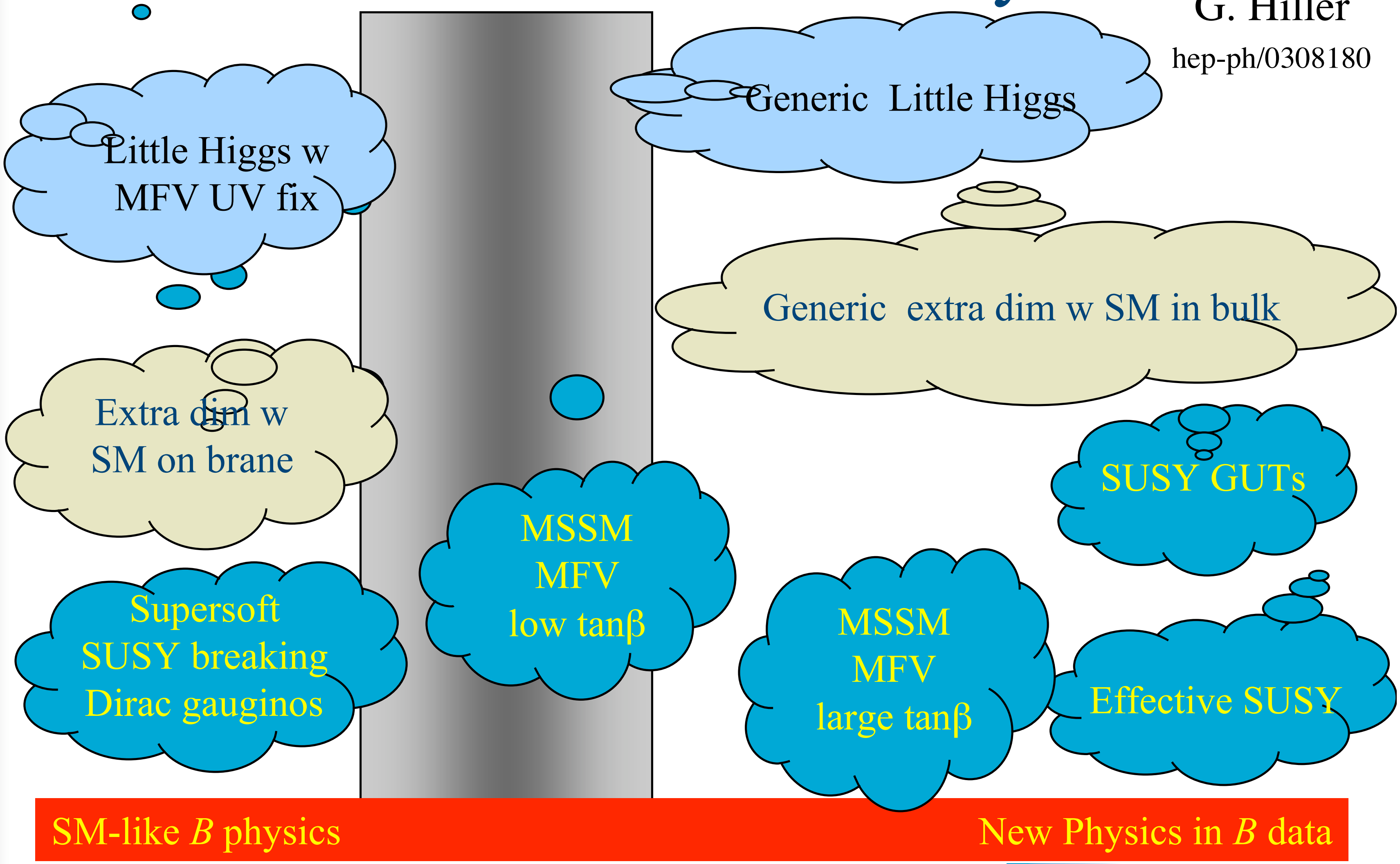
- LHC Discovers New Physics:
  - ¬ Λ_{NP} determined by ATLAS/CMS
  - ¬ Heavy Flavour probes flavour violation associated with "New Physics" – measure the new flavour parameters BTeV/LHCb determine flavour structure of "NP"

- LHC Discovers Nothing/SM Higgs
  - Heavy Flavours confirm SM predictions with ultra-precision

Need a flavour program regardless!

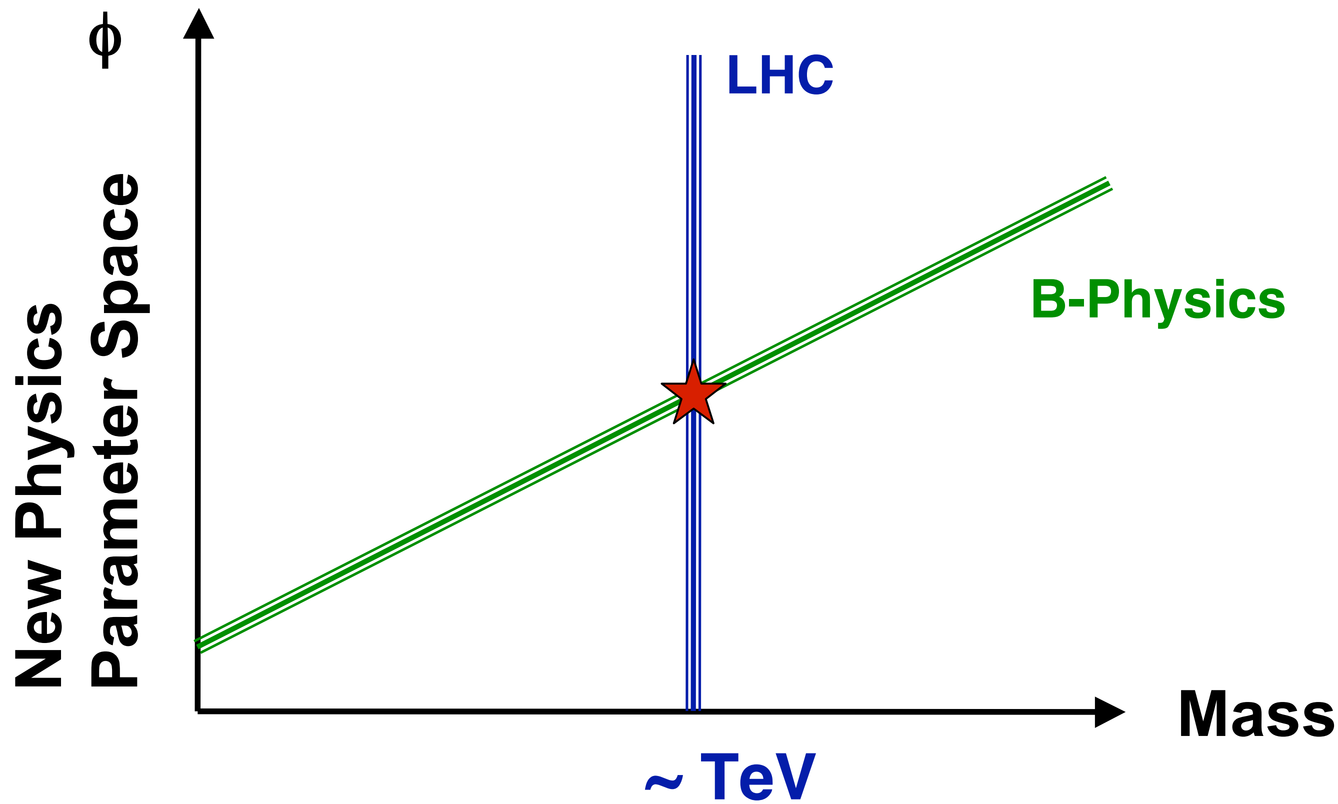
Flavour Violation in Models which address the Hierarchy

G. Hiller
hep-ph/0308180



Physics Beyond the SM: LHC?

Pictorial Example from Hewett (WIN03):



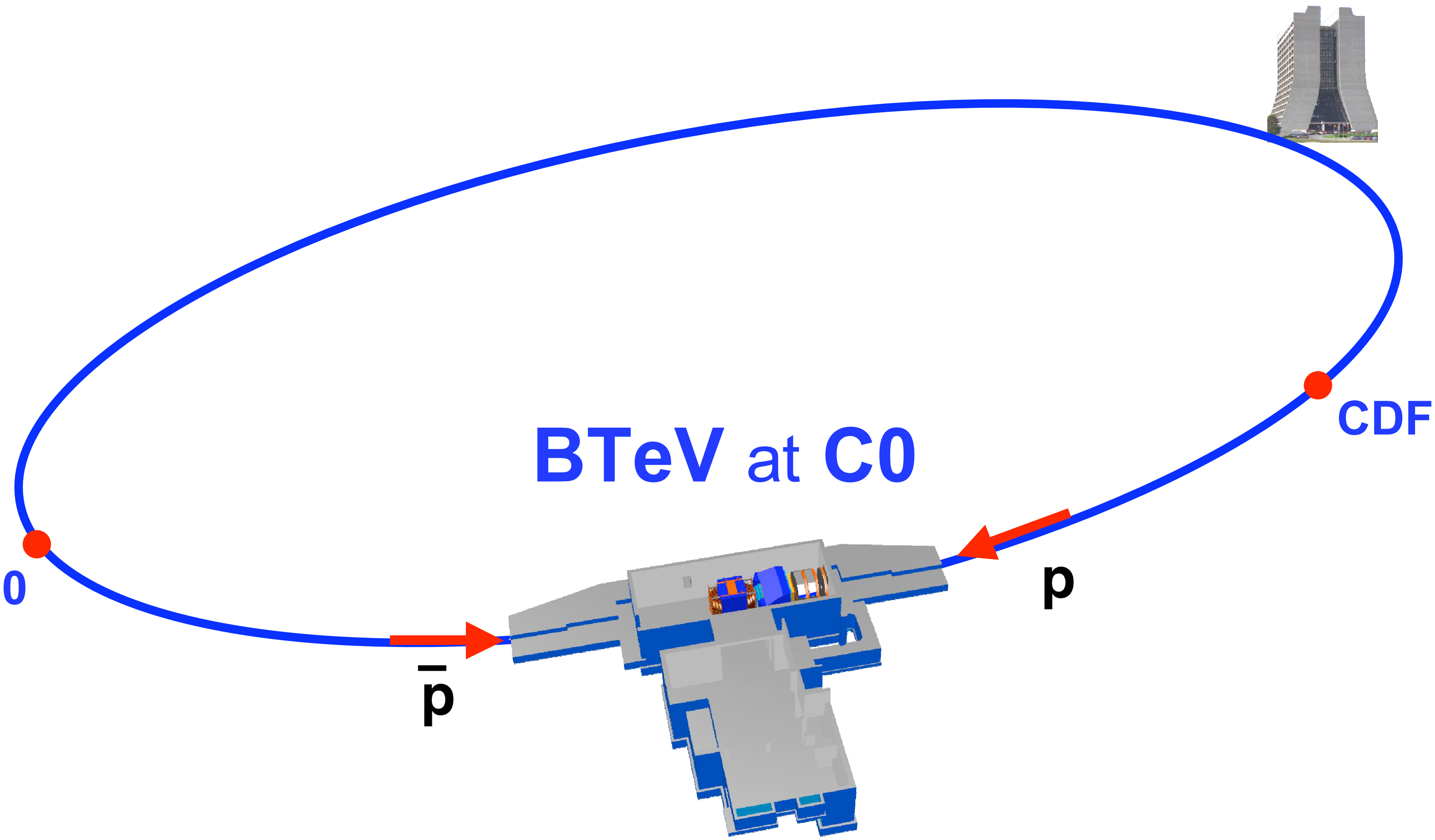
Complementary knowledge from LHC and B Decays!

Requirements for Measurements

- Precision: Large samples of decays, flavour tagged for CP-violation
- Comprehensive: B^+, B_d, B_s, B_c, b-baryon and charm decays
  Efficient reconstruction for "all" decays, including γ and π^0's
  Excellent flavour tagging

Physics Quantity	Decay Mode	Vertex Trigger	K/π Sep	γ Det	Decay Time σ
$\sin(2\alpha)$	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	✓	✓	✓	
$\cos(2\alpha)$	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$	✓	✓	✓	
$\sin(\gamma)$	$B_s \to D_s K^-$	✓	✓		✓
$\sin(\gamma)$	$B^0 \to D^0 K^-$	✓	✓		
$\sin(2\chi)$	$B_s \to J/\psi\eta$, $J/\psi\eta'$		✓	✓	✓
$\sin(2\beta)$	$B^0 \to J/\psi K_s$				
$\cos(2\beta)$	$B^0 \to J/\psi K^0$, $K^0 \to \pi l \nu$		✓		
x_s	$B_s \to D_s \pi^-$	✓	✓		✓
$\Delta\Gamma$ for B_s	$B_s \to J/\psi\eta^{(\prime)}$, K^+K^-, $D_s\pi$	✓	✓	✓	✓

BTeV at the Fermilab Tevatron



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J. Hietala, Y.Kubota, B.Lang, R.Poling, A.Smith

Nanjing Univ. (China):
T.Y.Chen, D.Gao, S.Du, M.Qi, B.P.Zhang, Z.Xi Zhang, J W.Zhao

New Mexico State Univ.:
V.Papavassiliou

Northwestern University:
J.Rosen

Ohio State University:
K. Honscheid, & H. Kagan

Univ. of Pennsylvania:
W. Selove

Univ. of Puerto Rico:
A.Lopez, H.Mendez, J.E.Ramirez W. Xiong

Univ. of Science & Tech. of China: G. Datao, L. Hao, Ge Jin, T. Yang, & X. Q. Yu

Shandong Univ. (China):
C. F. Feng, Yu Fu, Mao He, J. Y. Li, L. Xue, N. Zhang, & X. Y. Zhang

Southern Methodist Univ:
T. Coan, M. Hosack

Syracuse University:
M.Artuso, S.Blusk, J Butt, C.Boulahouache, O.Dorjkhaidav, J.Haynes, N.Menaa, R.Mountain, M.Muramatsu, R.Nandakumar, L.Redjimi, R. Sia, T.Skwarnicki, S.Stone, J.C.Wang, K. Zhang

Univ. of Tennessee:
T. Handler, R. Mitchell

Vanderbilt University:
W. Johns, P. Sheldon, E. Vaandering, M. Webster

Univ. of Virginia:
M. Arenton, S. Conetti, B. Cox, A. Ledovskoy, H. Powell, M. Ronquest, D. Smith, B. Stephens, Z. Zhe

Wayne State University:
G. Bonvicini, D. Cinabro, A. Shreiner

University of Wisconsin:
M. Sheaff

York University: S. Menary

Why do b and c Physics at Tevatron?

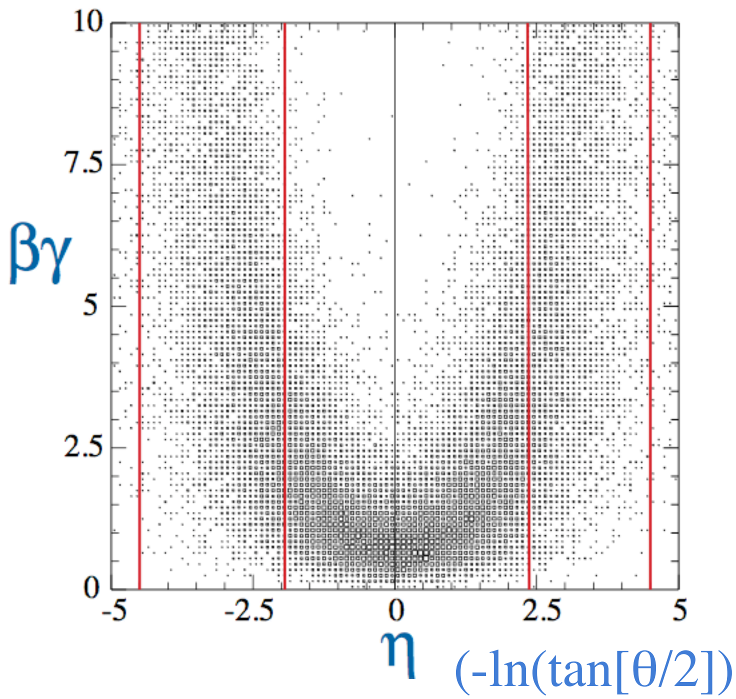
- Large samples of b quarks
  - Get ~ 4×10^{11} b hadrons per 10^7s at L = 2×10^{32} cm^{-2}s^{-1}
  - e^+e^- $\Upsilon(4S)$ get 2×10^8 B hadrons per 10^7s at 10^{34} cm^{-2}s^{-1}
- B_s, Λ_b and other b-flavored hadrons are accessible for study at the Tevatron
- Charm rates are ~ 10× larger than b rates

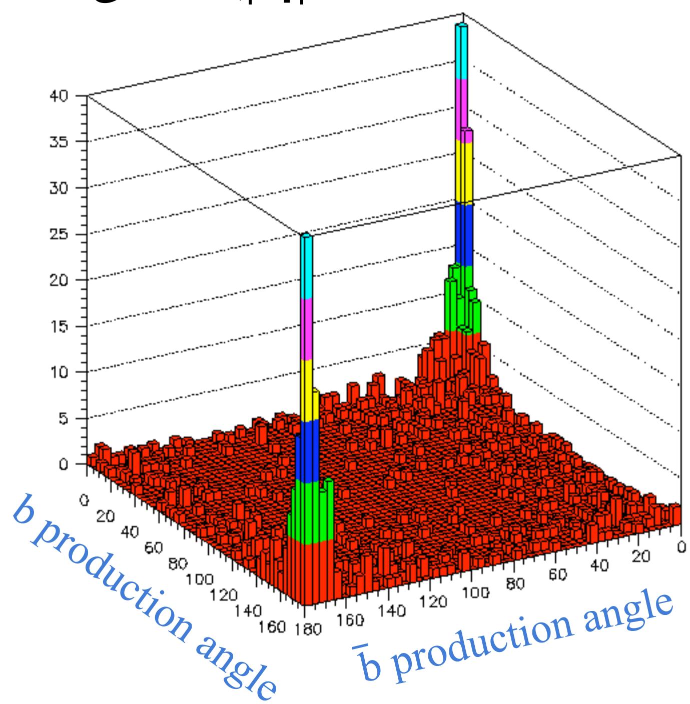
Some assumed parameters for the Tevatron for simulations:

- CMS energy = 2 TeV and L = 2×10^{32} cm^{-2}s^{-1}
- Time/crossing = 132 ns originally, updating for 396 ns
  (6-9 interactions/crossing - Poisson mean)
- Interaction region σ_z= 30cm and $\sigma_{x,y}$= 50μm
- $\bar{b}b$ cross section = 100 μb

Why look in the Forward Region?

BTeV detects in the forward region (|η| from 1.9 to 4.5)





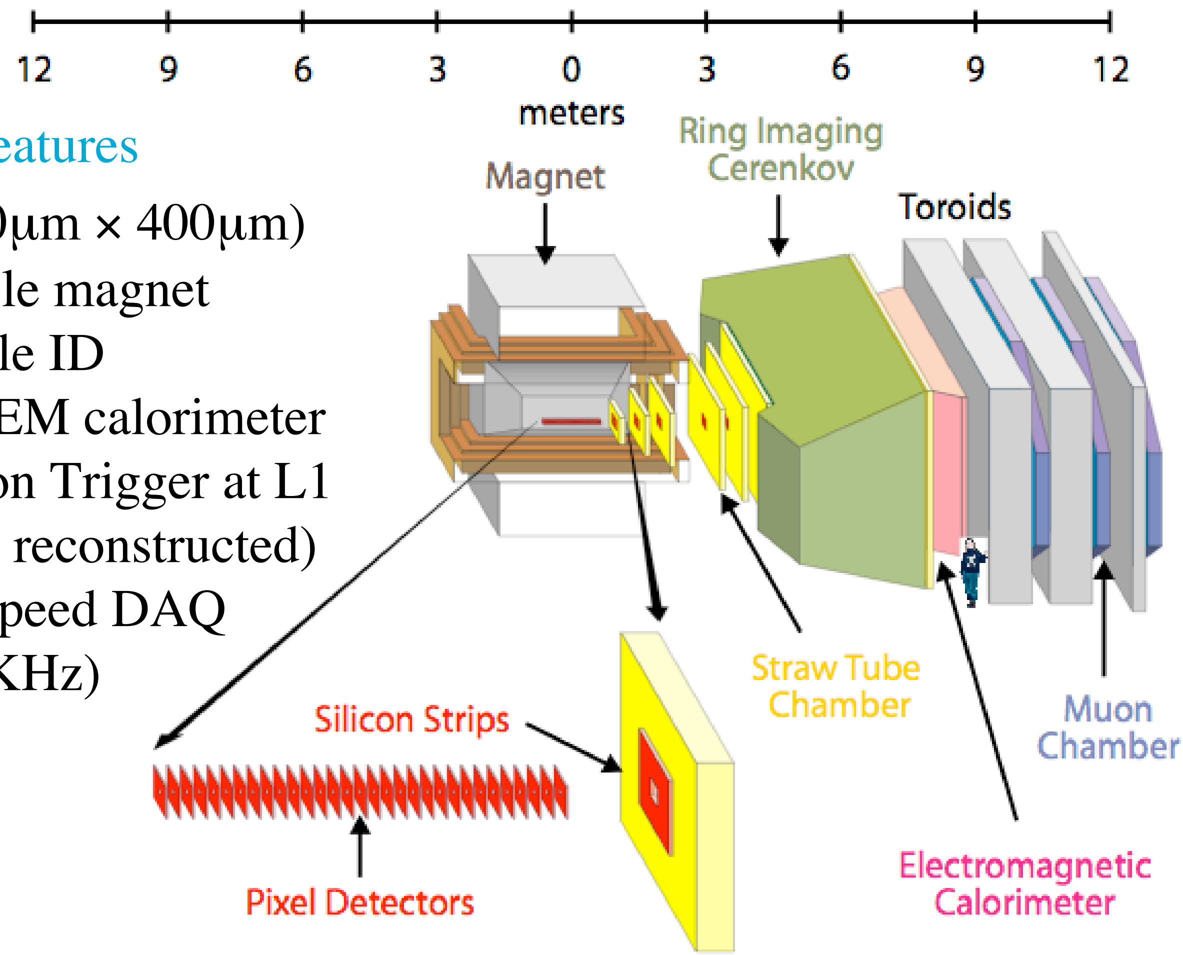
- Better decay length separation
- Less multiple scattering

- More BB in the Detector
- Better away side tagging

The BTeV Detector

Main/Unique Features

- Vertex pixel (50μm × 400μm) detector in dipole magnet
- RICH for particle ID
- $PbWO_4$ crystal EM calorimeter
- Vertex separation Trigger at L1 (primary vertex reconstructed)
- Powerful high speed DAQ (output up to 4KHz)



Projected Performance

and

Comparisons to existing and Future Experiments

Physics Reach CKM in 10^7 s (Model Independent)

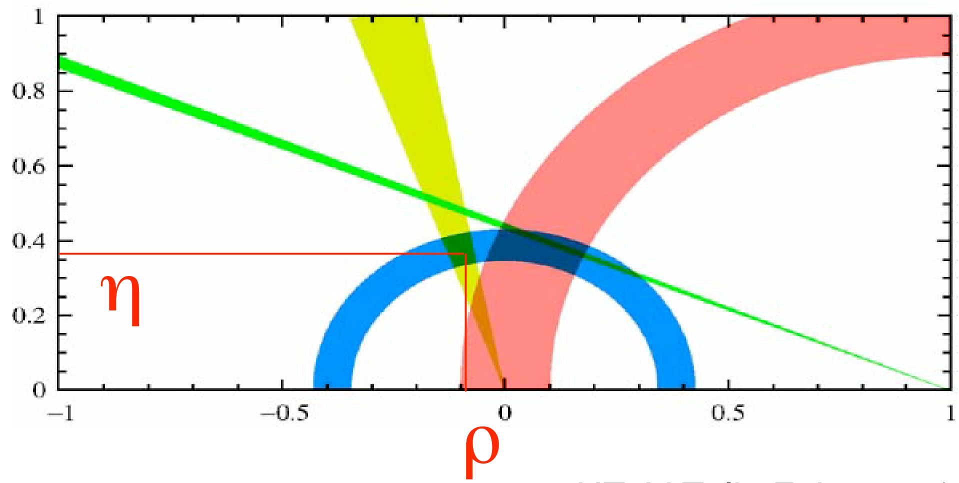
Decay	$\mathcal{B}(B)$ ($\times 10^{-6}$)	# Events	S/B	Parameter	Error or (Value)
$B_s \to D_s K^-$	300	7500	7	$\gamma - 2\chi$	8^o
$B_s \to D_s \pi^-$	3000	59,000	3	x_s	(75)
$B^0 \to J/\psi K_S$ $J/\psi \to l^+ l^-$	445	168,000	10	$\sin(2\beta)$	0.017
$B^0 \to J/\psi K^0$, $K^0 \to \pi l \nu$	7	250	2.3	$\cos(2\beta)$	~0.5
$B^- \to D^0 (K^+\pi^-) K^-$	0.17	170	1	γ	13^o
$B^- \to D^0 (K^+K^-) K^-$	1.1	1,000	>10		
$B_s \to J/\psi\, \eta$	330	2,800	15	$\sin(2\chi)$	0.024
$B_s \to J/\psi\, \eta'$	670	9,800	30		
$B^0 \to \rho^+\pi^-$	28	5,400	4.1	α	$\sim 4^o$
$B^0 \to \rho^0\pi^0$	5	780	0.3		

Reach CKM in 10^7s (Model Dependent)

Model dependent measures of γ, may be useful for ambiguity resolution

Decay	B(B) ($\times10^{-6}$)	# Events	S/B	Parameter	Error
$B^- \to K_S \pi^-$	12.1	4,600	1	γ	<4° +
$B^0 \to K^+\pi^-$	18.8	62,100	20		Theory errors
$B^0 \to \pi^+\pi^-$	4.5	14,600	3	Asymmetry†	0.030
$B^0 \to K^+ K^-$	17	18,900	6.6		0.020

† Can determine γ assuming d ↔ s symmetry, therefore model dependent



Clean measurements of γ: ±5°

- Assume $\Delta m(B_d)/\Delta m(B_s)$ known to ±5% from CDF and D0
- Assume sin(2β) known to 0.02 from 1000 fb^{-1} BaBar and Belle
- γ measured to ±5° by BTeV

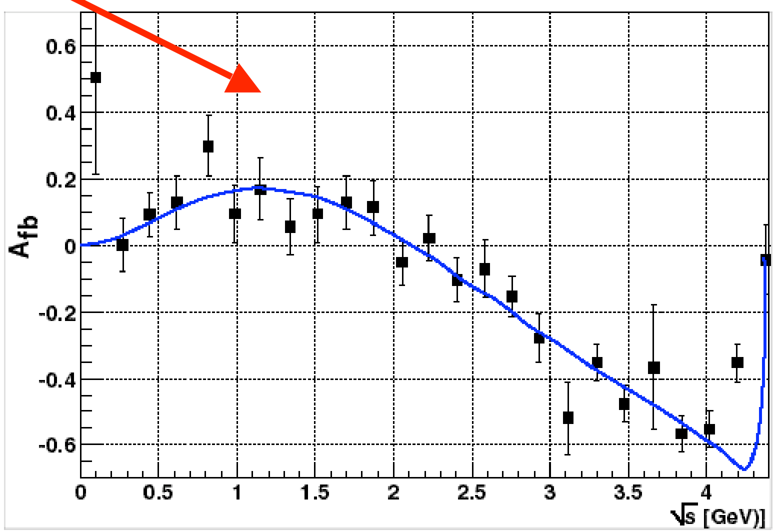
Need many comparisons in reality!

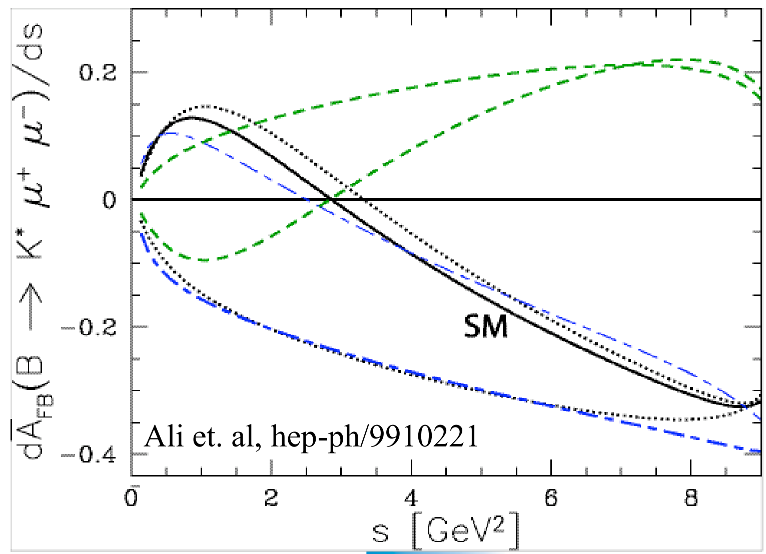
Physics Reach: Rare Decays

Decay	B (10^{-6})	Signal	S/B	Physics
$B^o \to K^{*o}\mu^+\mu^-$	1.5	2530	11	polarization & rate
$B^- \to K^-\mu^+\mu^-$	0.4	1470	3.2	rate
$b \to s\mu^+\mu^-$	5.7	4140	0.13	rate: Wilson coefficients

BTeV "data" compared to Burdman et al. Calculation for $K^*l^+l^-$

One year for $K^*l^+l^-$ could be enough to determine if New Physics is present





Charm Physics Potential

Flexible trigger and high rate DAQ - potential to find New Physics

- D^0-$\overline{D}^0$ Mixing: Box diagram: $\Delta m_D^{SD}/\Gamma < 1\times10^{-4}$
  LD Dispersive: $\Delta m_D^{LD}/\Gamma \sim 2\times10^{-4}$
  LD HQET: $\Delta m_D^{LD}/\Gamma \sim (1 \text{ to } 2)\times10^{-5}$
  SM Contribution: $\Delta m_D^{SM}/\Gamma < 1\times10^{-4}$
  Current experimental limit $\Delta m_D/\Gamma < 0.1$ Lots of Discovery room!

- CP Violation: Possibly observe SM CP violation in charm!
  SM: $A_{CP} \approx 2.8\times10^{-3}$ for $D^+ \rightarrow \overline{K^{*0}}K^+$
  $A_{CP} \approx -8.1\times10^{-3}$ for $D_s^+ \rightarrow K^{*+}\eta'$
  Expect $\sigma(A_{CP}) = 1\times10^{-3}$ for 10^6 background-free events
  Excellent D* tag (efficiency ≈ 25%)
  Geant simulation gives # reconstructed $D^0 \rightarrow K\pi > 10^8$

BTeV has the necessary detectors, trigger and DAQ for charm

Comparisons to Belle/BaBar

- No B_s, B_c and Λ_b at B-factories (no comprehensive study)
- Number of flavor tagged $B^0 \to \pi^+\pi^-$ ($BR=0.45\times10^{-5}$)

	$L(cm^{-2}s^{-1})$	σ	$\#B^0/10^7s$	ε_{rec}	εD^2	#tagged
e^+e^-	10^{34}	1.1nb	1.1×10^8	0.45	0.26	56
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.021	0.1	1426

- Number of $B^- \to \overline{D}^0 K^-$ (Full product $BR=1.7\times10^{-7}$)

	$L(cm^{-2}s^{-1})$	σ	$\#B^0/10^7s$	ε_{rec}	#
e^+e^-	10^{34}	1.1nb	1.1×10^8	0.4	5
BTeV	2×10^{32}	100μb	1.5×10^{11}	0.007	176

Events in New Physics Modes: Comparison with B-Factories

Mode	BTeV (10^7s)			B-Factory (500 fb^{-1})		
	Yield	Tagged	S/B	Yield	Tagged	S/B
$B_s \to J/\Psi\eta^{(\prime)}$	12650	1645	>15	-	-	-
$B^- \to \phi K^-$	11000	n/a	>10	700	700	4
$B^0 \to \phi K_s$	2000	200	5.2	250	75	4
$B^0 \to K^* \mu^+\mu^-$	2530	n/a	11	~50	~50	3
$B_s \to \mu^+\mu^-$	6	0.7	>15	-	-	-
$B^0 \to \mu^+\mu^-$	1	0.1	>10	0	-	-
$D^{*+} \to D^0\pi^+, D^0 \to K\pi^+$	$\sim 10^8$	$\sim 10^8$	large	8×10^5	8×10^5	large

Comparison to Super-KEK

- KEK-B plans for $L=10^{35}$ $cm^{-2}s^{-1}$ in 2007, (10× original design)
- Numbers in previous tables still not competitive with BTeV
- Problems for detectors (See E2 report at 2001 Snowmass)

(Zhao et al., hep-ph/0201047)

Comparison to Super-BaBar

- Proposal for $L=10^{36}cm^{-2}s^{-1}$ (>100× original design)
- Would be competitive with BTeV in B^0 and B^+ Physics
- Still could not do B_s, B_c and Λ_b
- Serious technical problems to overcome for both the machine and detector (see M2 report at Snowmass)

(Henderson, Oide and Seeman, eConf C010630:M2001, 2001)

- We believe the cost will far exceed that of BTeV (Relatively recent HEPAP subpanel mentions $500M)

Comparison to Central Detectors CDF, D0, ATLAS, CMS

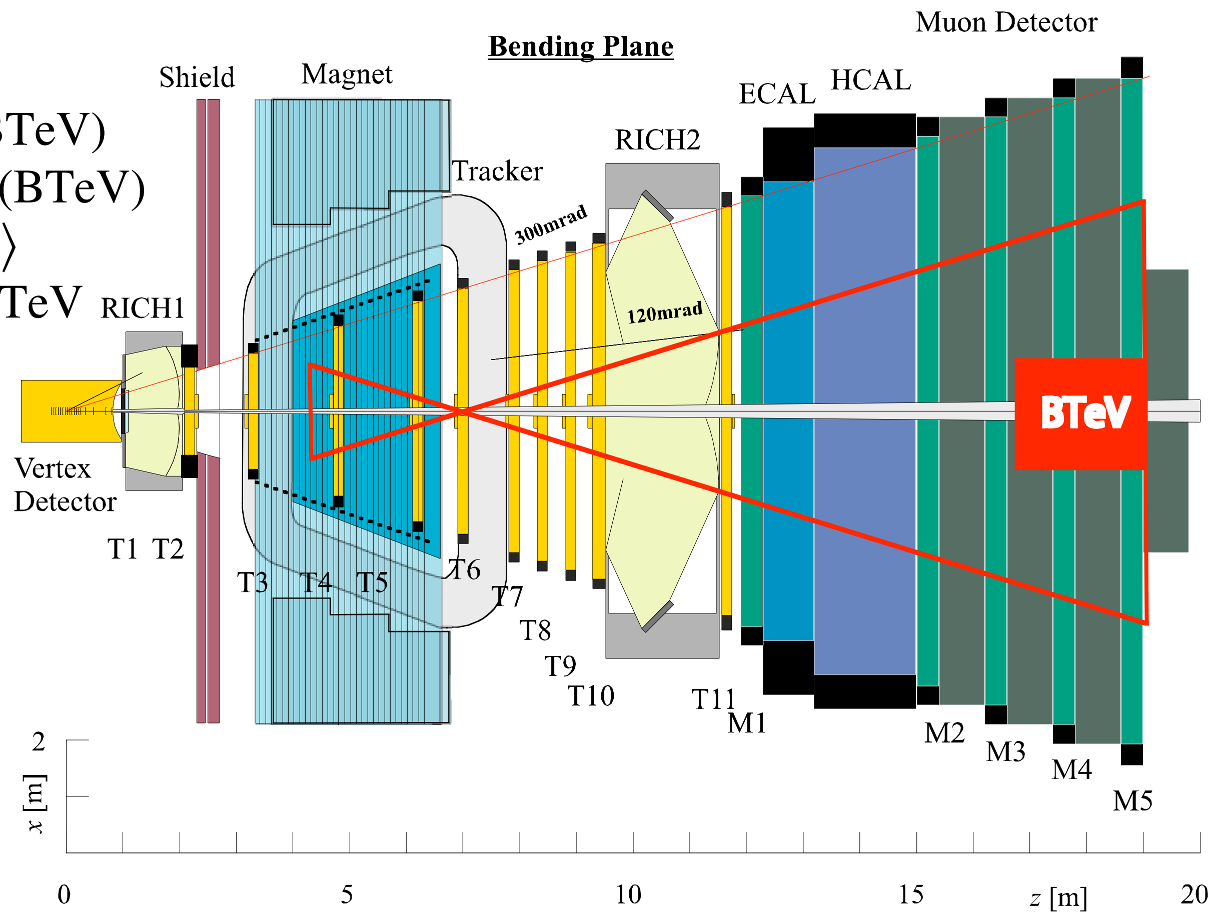
- Physics reach for b and c is beyond CDF, D0, ATLAS and CMS (these are not optimized for b-physics)
  - Particle ID over large p range (S/N [b/c] and flavor tagging)
  - γ and π^0 detection (room for crystal calorimeter)
  - Trigger at Level 1 - purely hadronic decays
  - High rate DAQ - more comprehensive b and c decays
  - Large η (boost) - background rejection and time resolution
- Difficult to get numbers to c.f. (triggerable, BR, ε, σ, tagged, S/N)

Mode	CDF [/D0] ($2\ fb^{-1}$)		ATLAS ($30\ fb^{-1}$)		CMS ($30\ fb^{-1}$)		BTeV ($10^7 s$)	
	Yield	S/N	Yield	S/N	Yield	S/N	Yield	S/N
$B_s \to D_s \pi^-$			6750	?	-	-	59000	
$B_s \to D_s K^-$	850	0.2	-	-	-	-	7700	7
$B_s \to \mu^+\mu^-$			27	0.3	21	7	6	>15
$B^0 \to K^* \mu^+\mu^-$			2000	7	-	-	2530	11

Comparison to LHCb

- Competition is LHCb
  $\sigma_{bb}(\text{LHCb}) = 5\times\sigma_{bb}(\text{BTeV})$
  $\sigma_{tot}(\text{LHCb}) = 1.6\times\sigma_{tot}(\text{BTeV})$
- ⟨Interactions/Crossing⟩
  ~ much lower than BTeV

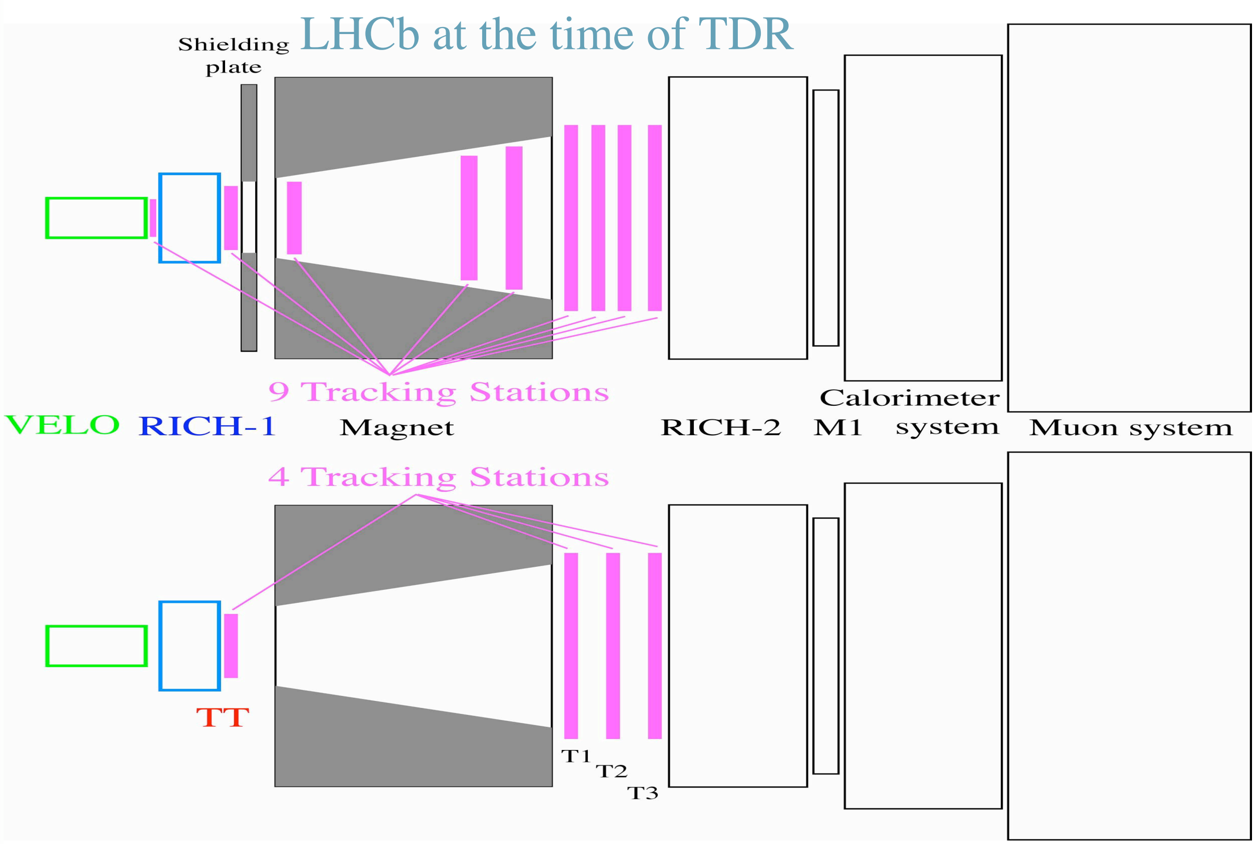
However BTeV has Many Advantages!



Comparison to LHCb II

- BTeV is designed around a pixel detector with less occupancy, allows for a detached vertex trigger at the first level trigger
  - Large samples of rare hadronic and charm decays
  - BTeV can run with multiple interactions per crossing
- BTeV vertex detector in magnetic field allows rejection of low momentum (high MCS) tracks in the trigger
- BTeV has a (20×) higher rate DAQ - more b and c decays
- BTeV will have a much better EM calorimeter - more comprehensive study of decays
- LHCb completed an extensive change from TDR-design (Sep. 2003):
  - Reduced # silicon planes and thickness, # tracking stations
  - Put magnetic field in interaction region (remove shield-RICH)
  - Added high p_T only trigger (for $B \rightarrow h^+h^-$)
  - Allow multiple interactions per crossing

Changes from TDR to LHCb Light



Reoptimized LHCb (code name "light")

Reduction of material

- VELO sensor
  - 25 → 21 stations
  - 300 → 220 μm
- Beam pipe
  - Al → Al/Be alloy
- RICH1 mirror
  - glass → composite
  - improved support
- Tracking stations
  - 9 → 4

Material up to RICH-2
60 → 40% X_0
20 → 12% λ_I

\+ L1 Trigger optim.

Comparison to LHCb III

- Compare to preliminary (Sept 2003) LHCb light #s

Mode	BR (10^{-5})	LHCb Untag Yield		BTeV (Yield scaled to BR)
		TDR	Light(*)	
$B_s \to D_s \pi^-$	300	86000	100000	59000
$B_s \to D_s K^-$	23	6000	6200	5900

- Compare to LHCb TDR #s (LHCb light #s ready in fall ~TDR #s)

Mode	BR	LHCb		LHCb-light(*)		BTeV	
		Yield	S/B	Yield	S/B	Yield	S/B
$B_s \to J/\psi\eta^{(\prime)}$	1.0×10^{-3}	-	-	7000	0.2	12650	>15
$B^0 \to \rho^+\pi^-$	2.8×10^{-5}	2140	0.8	3600	0.14	5400	4.1
$B^0 \to \rho^0\pi^0$	0.5×10^{-5}	880	?			776	0.3

- BTeV superior for photons/π^0 and more comprehensive data set

BTeV R&D Status

and

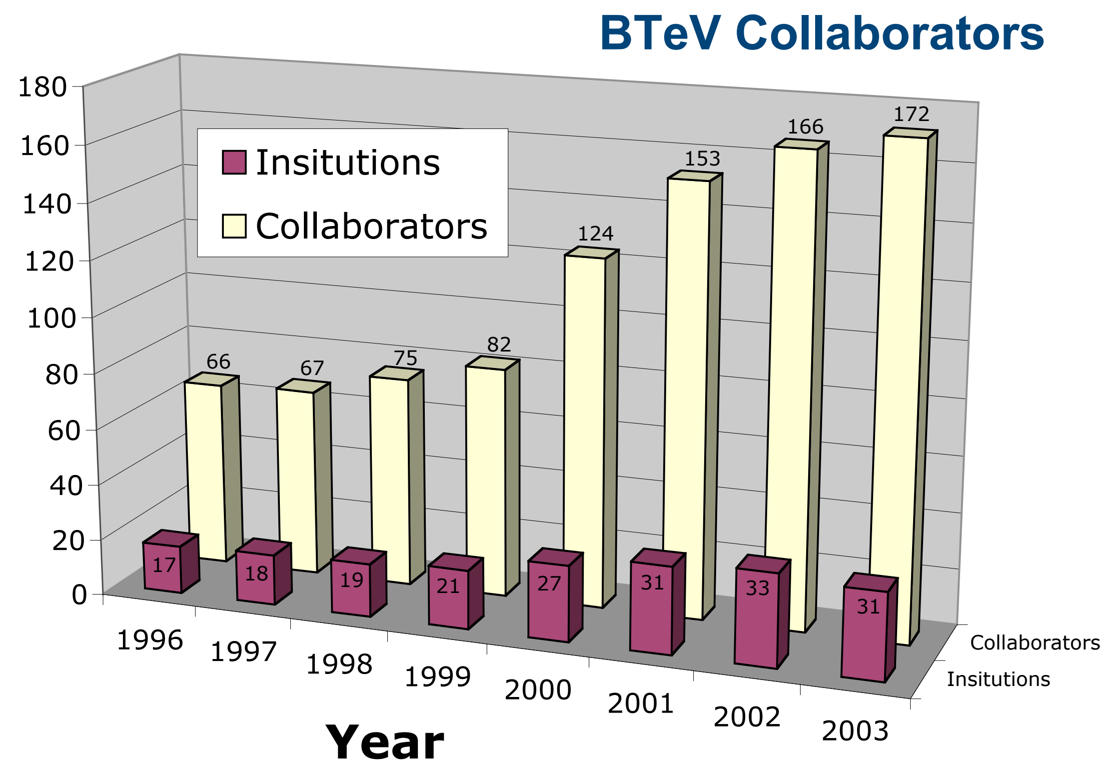
Current Approval Status

Brief History and Status of BTeV

- May 1997 - EOI, 161 pages
- Dec. 1997 - Addendum, 62 pages - address PAC concerns
  ⇒ BTeV becomes a R&D project
- May 1999 - Preliminary TDR, 373 pages (full BTeV)
- May 2000 - Proposal, 429 pages, submitted to Fermilab
  June 2000 ⇒ PAC unanimously recommends Stage 1 approval
  ⇒ Approval from Director (2-arm)
- Mar. 2002 - Proposal update, 126 pages (request from Lab, 1-arm)
  ⇒ PAC unanimously recommends approval of descoped BTeV
  ⇒ Approval from Director (1-arm)
- Oct. 2002 - Fermilab conducts cost review of BTeV (Temple)
- Mar. 2003 - Review of BTeV by P5
  ⇒ Oct. 2003 - P5 supports building BTeV and recommends earliest construction
  ………..

Continual and Growing interest in BTeV

- Despite long review and approval process and problems for universities getting funding (e.g. for R&D):

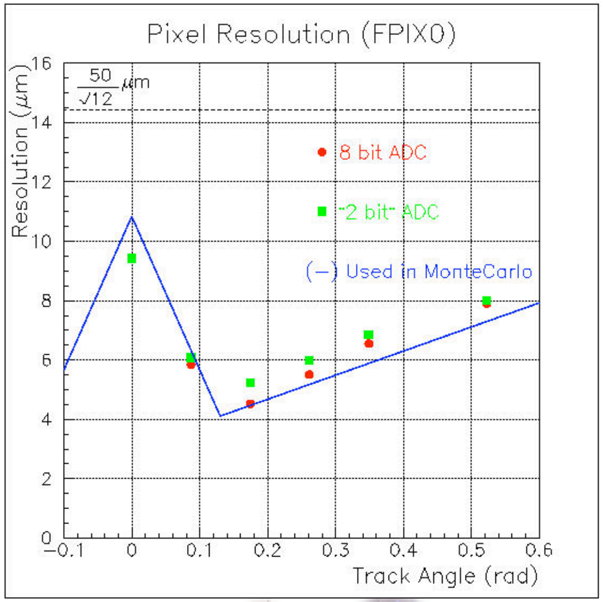


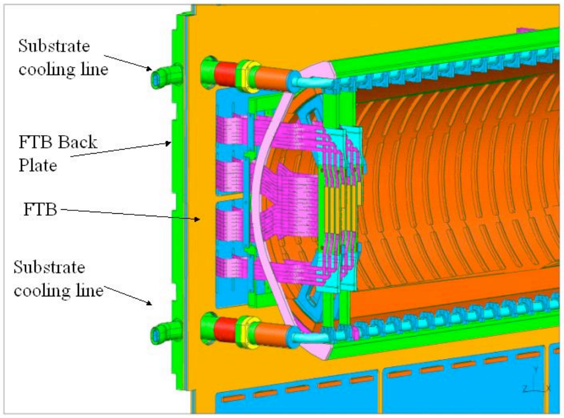
Most of these are senior members - expect to grow to 300.

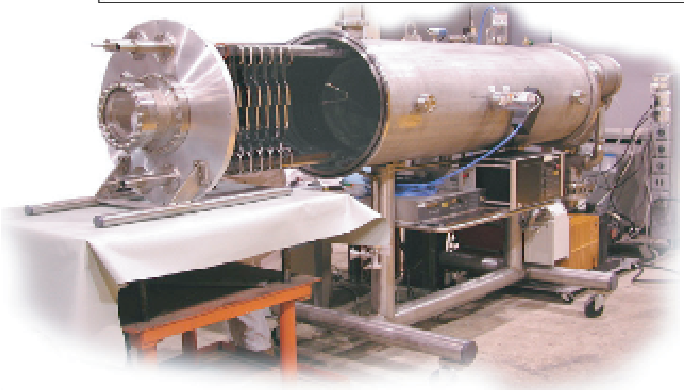
- There is very strong interest in the physics and technology of BTeV

Pixel Vertex Detector

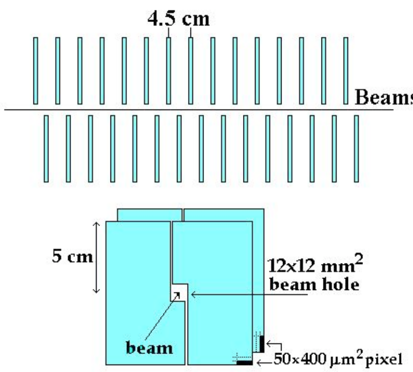
- **Achieved design (5-10 micron) resolution in 1999 FNAL test beam run.**
- **Demonstrated radiation hardness in exposures at IUCF.**
- **The final readout chip has been bench tested and will undergo final testing in FNAL test-beam in ~~2003~~ 2004**
- **Removed all water-vacuum joints in the cooling system in favor of thermopyrolitic graphite cold fingers**



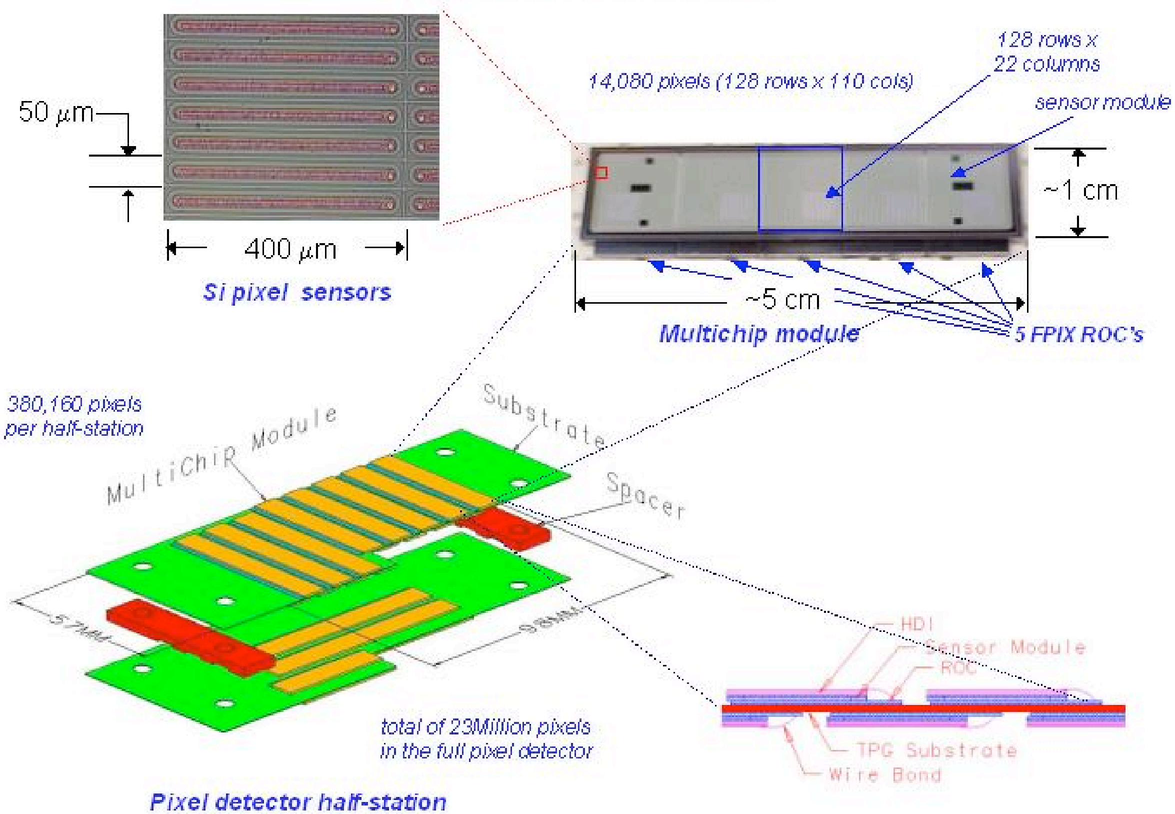




Pixel Vertex Detector II

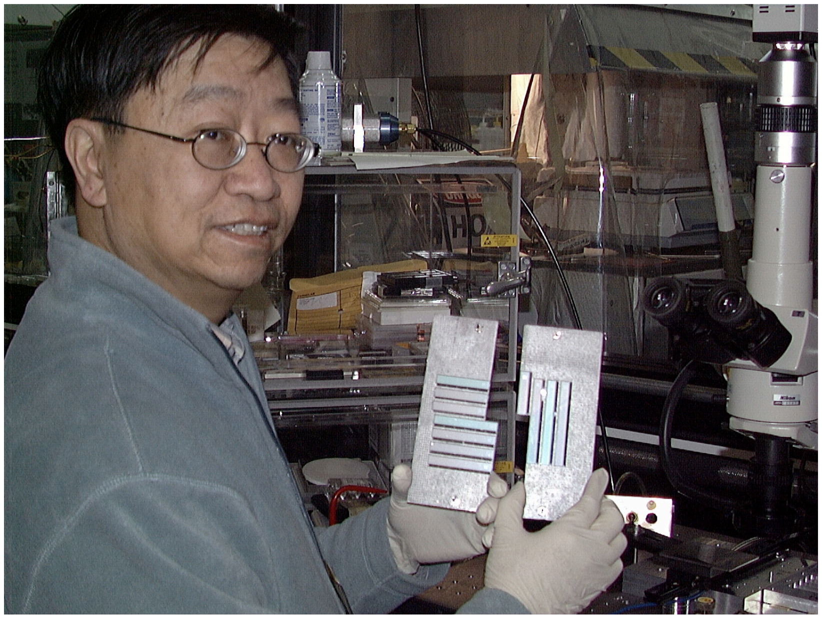


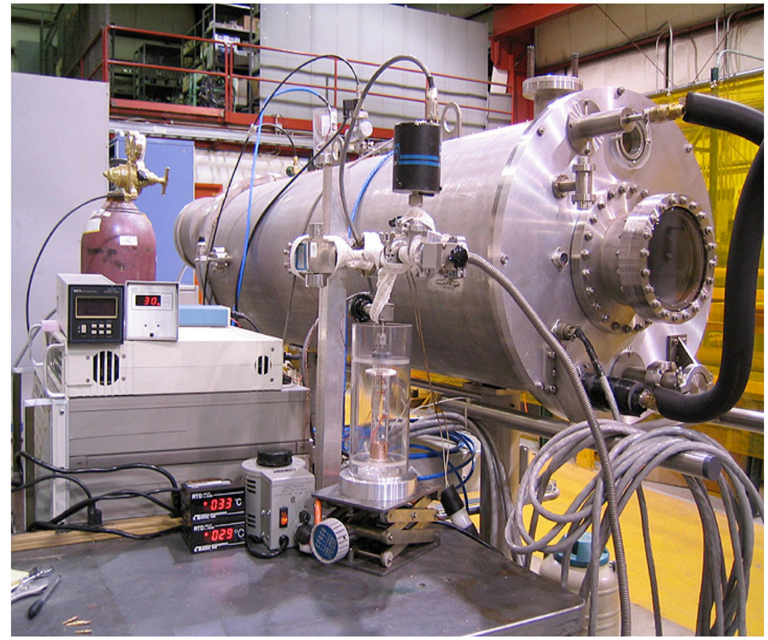
Half-Station Assembly



Will test first multichip Modules in 2004 FNAL Test beam

Pixel Vertex Detector III





Still working on many challenges (amount of material, beam, vacuum):

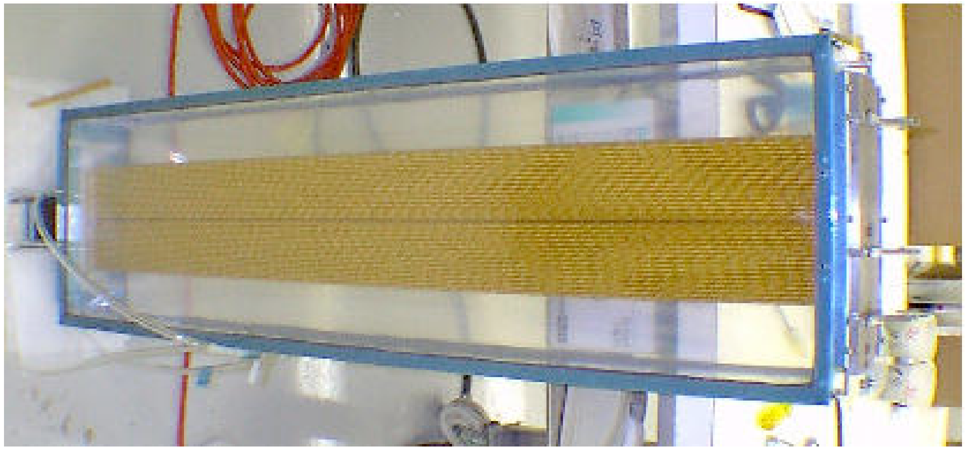
Sensors, Readout chip, HDI, …

Mechanical support, vacuum, cooling, RF shielding, …

Integration and testing, Beam test preparation, …

Forward Tracking

- 7 Tracking stations each with:
  - 100µm silicon strip detector for small angles (high occupancy region)
  - 4mm diameter straw detector with 27cm × 27cm hole
    (3 views per station and 3 layers view)
- Predicted performance - better than 1% resolution over full p and θ range



Prototype for 2004 FNAL beam test

Drawing of forward microstrip tracker

- Lots of experience with silicon trackers at Milan

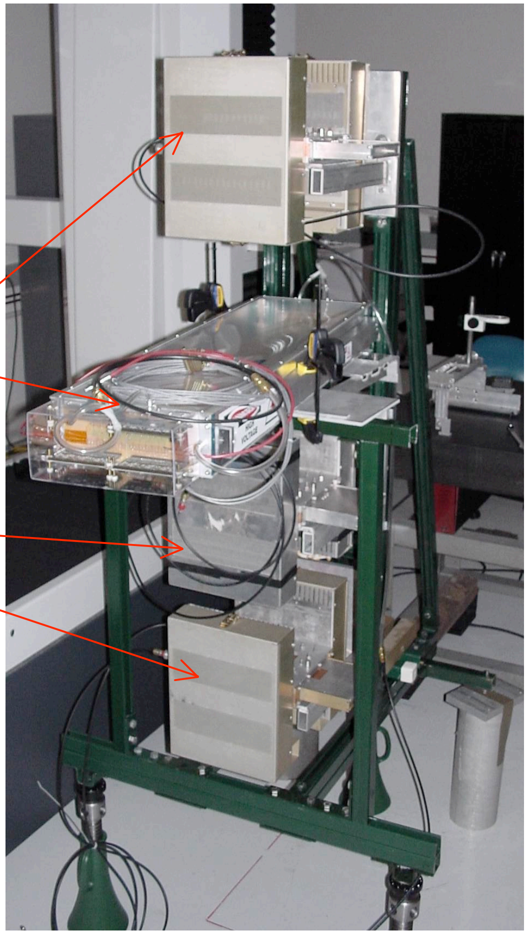
Forward Tracking II

Cosmic ray test stand at Lab 3
Also preparing for beam tests

Straw Prototype

E690 High Rate Drift Chambers (1mm pitch)

3x 64 channels (6.4 cm width)

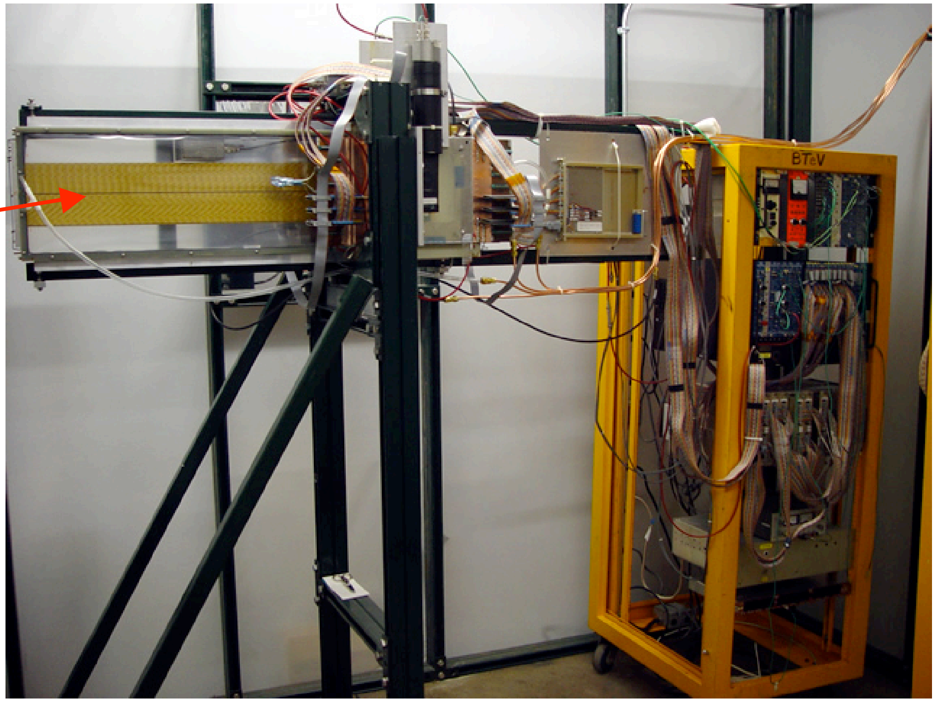


Forward Tracking III

Test stand at MTest

Straw Prototype
3x 64 channels
(6.4 cm width)

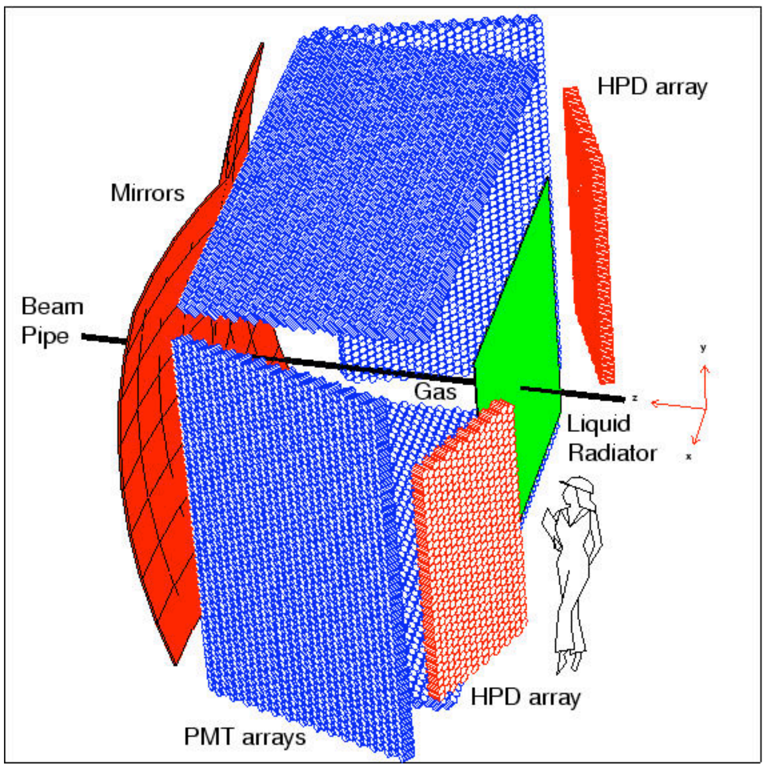
Calibration using E831 Silicon strip detectors and pixel detectors



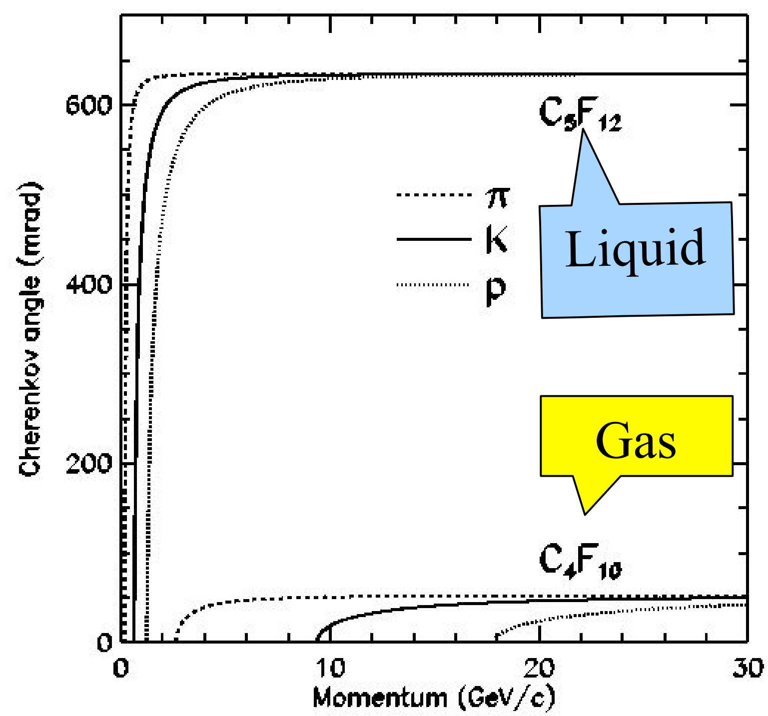
Still looking at silicon/straw detector design due to 396 ns
Still looking at straw construction, Forward silicon design

Ring Imaging Cherenkov Counter

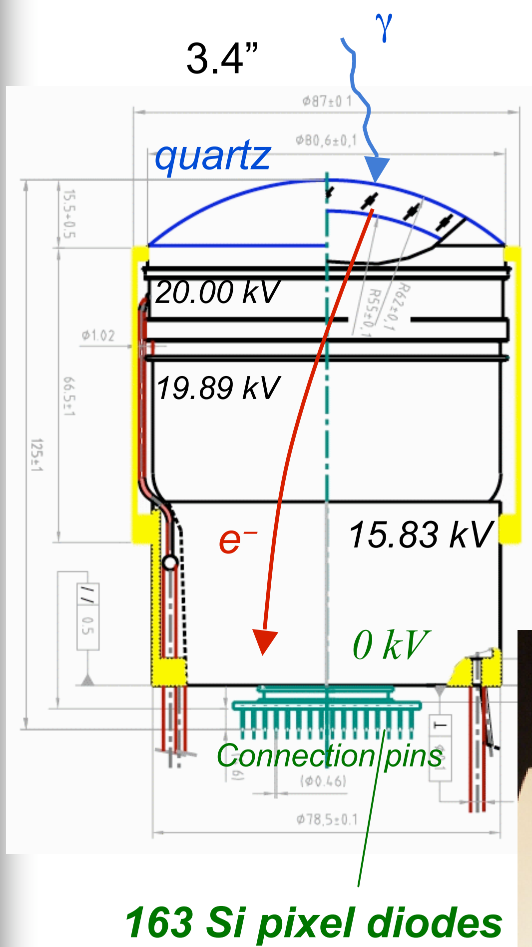
- Gas radiator (C_4F_{10}) detected on planes of Hybrid Photodiodes
- Liquid radiator (C_5F_{12}) detected on array of side mounted PMTs (replaced aerogel radiator option detected on same HPDs)



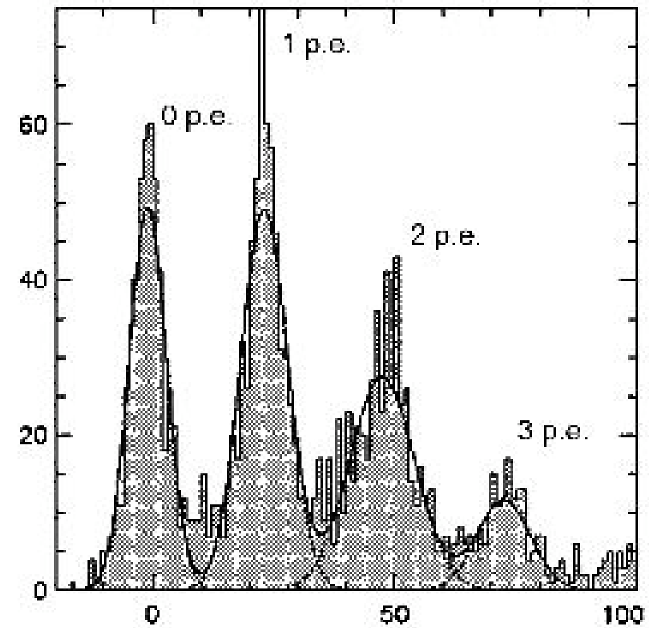
Cherenkov angle vs P

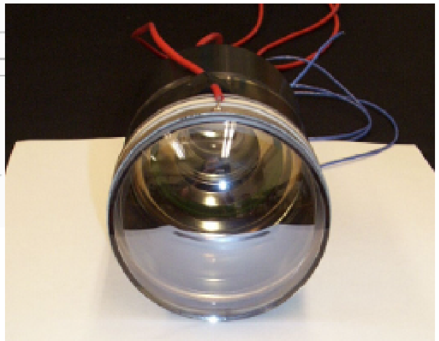


Ring Imaging Cherenkov Counter II



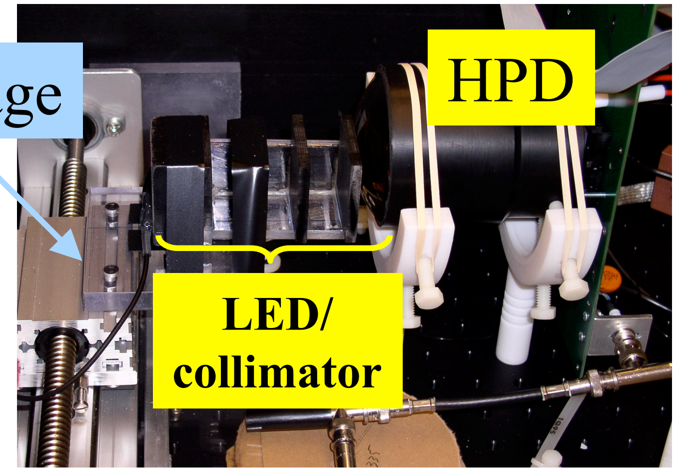
- Developed a 163 pixel HPD
- Bench test at Syracuse showing pulse height distribution from prototype
- Have 15 for beam test



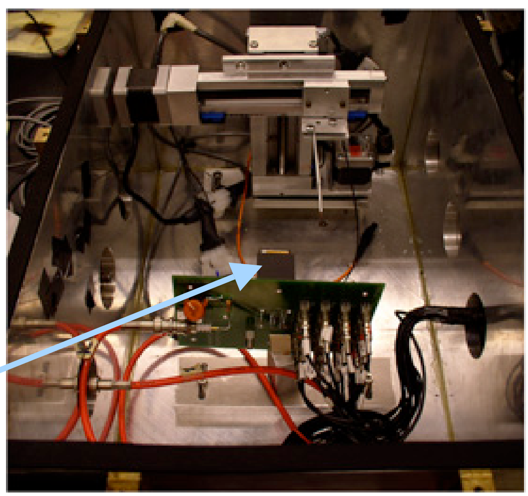


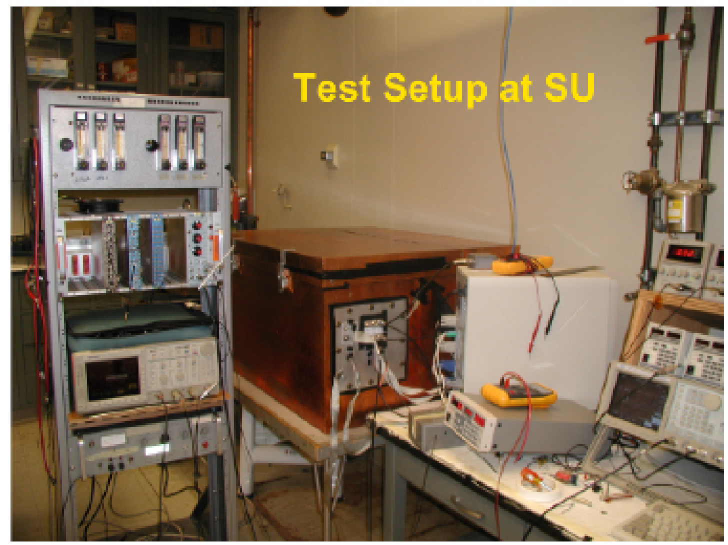
Now have a Multi-anode-PMT alternative

RICH HPD and MAPMT Tests



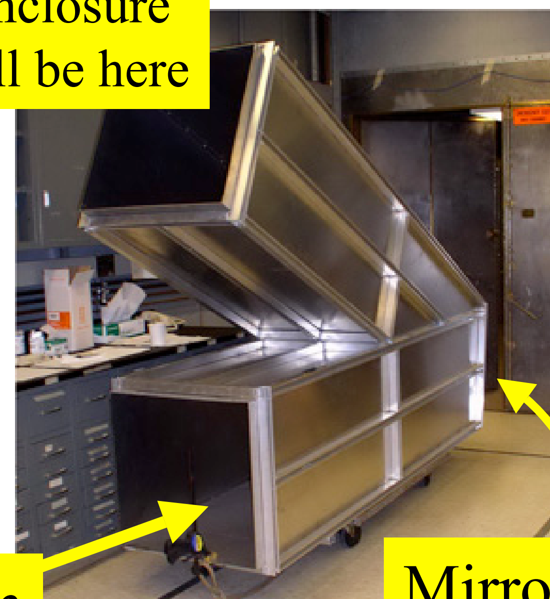
Scans on the bench of HPDs and MAPMTs at Syracuse





Beam Tests for the RICH

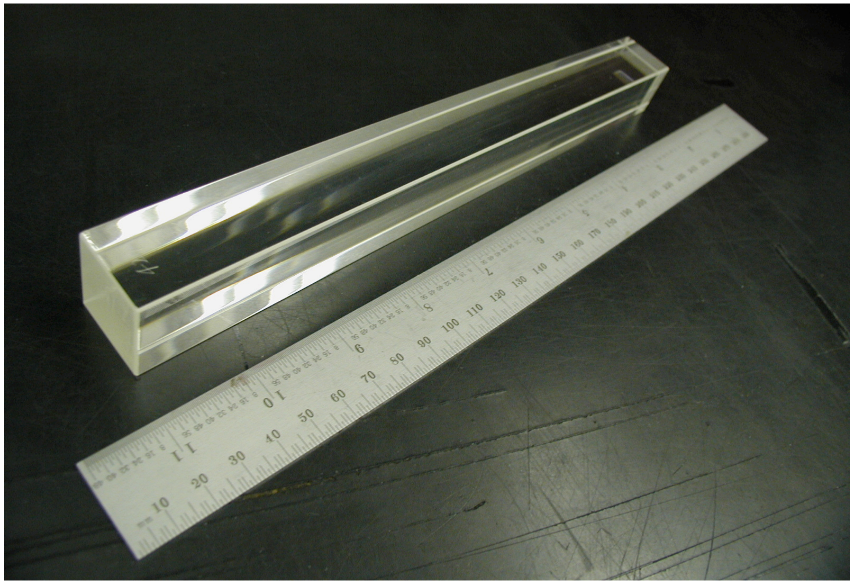
Tests of radiator, mirror, photon detectors

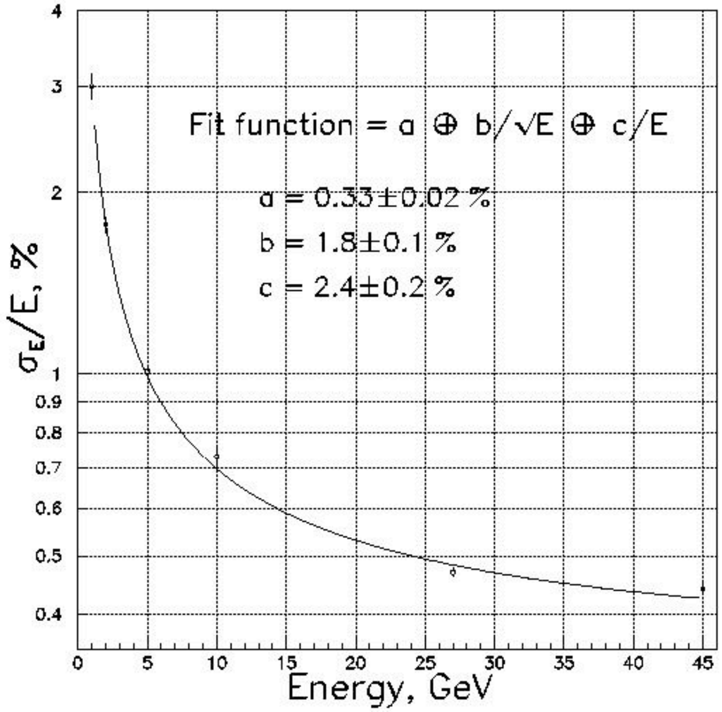


Enclosure for RICH beam test

Lead Tungstate EM Calorimeter

- $PbWO_4$ 28×28mm^2 × 22cm crystals pioneered by CMS, but BTeV uses PMTs
- Excellent energy and spatial resolution
- Resolution measured at IHEP/Protvino beam tests (Stochastic term = 1.8%) (Total of 3 beam tests at Protvino)

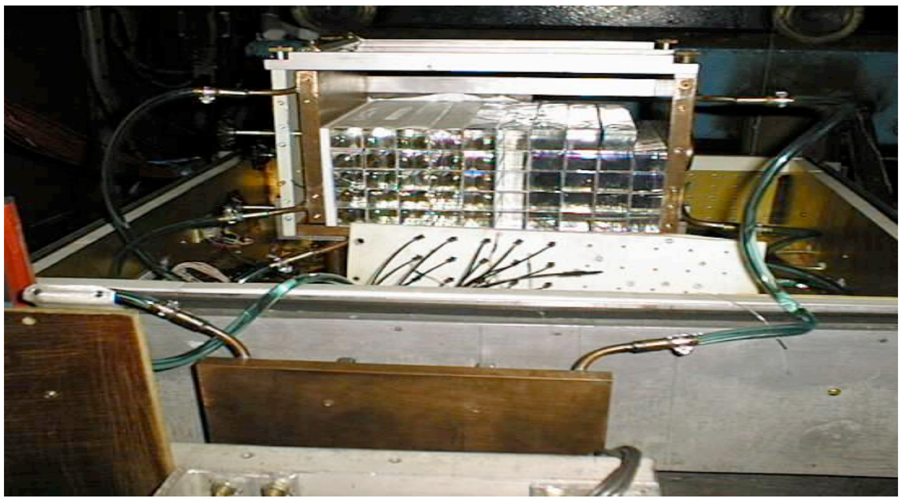


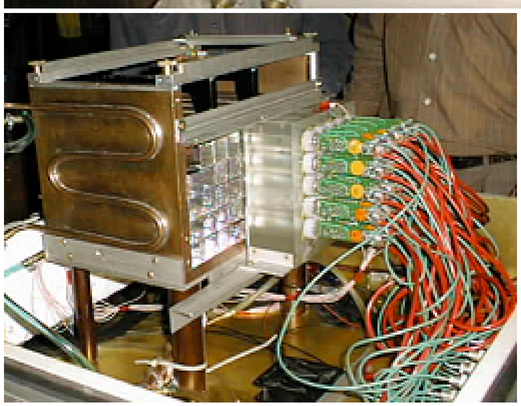


We have multiple possible vendors from Bogoriditsk, Russia and Shanghai, China

Lead Tungstate EM Calorimeter II

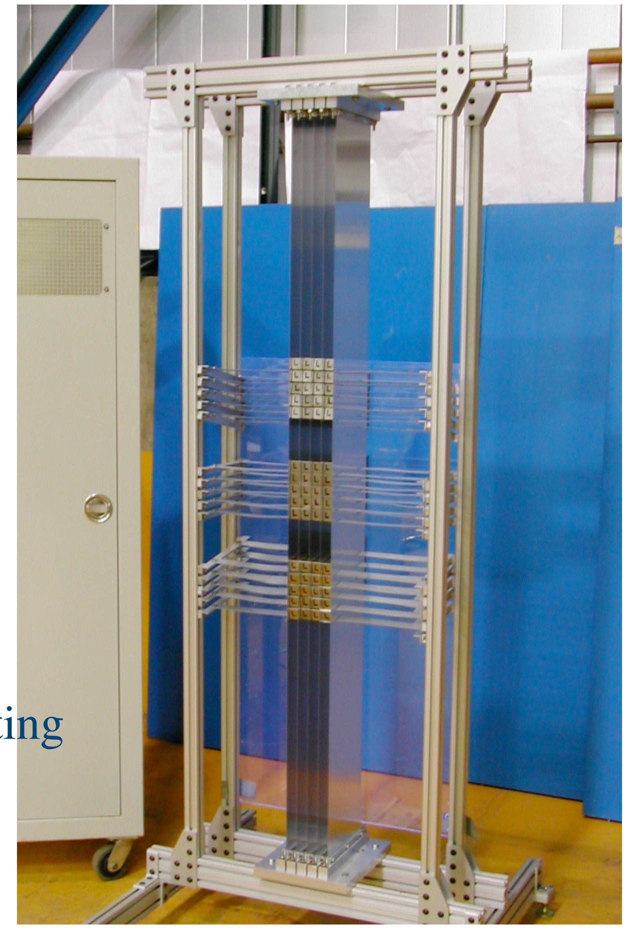
Stacks of blocks in temperature controlled box
For testing in Protvino in March 2002





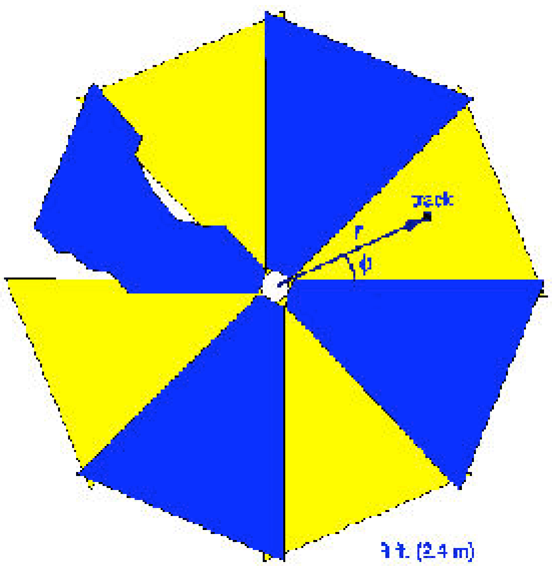
Half-height prototype EMCAL support. Testing crystal loading and installation details

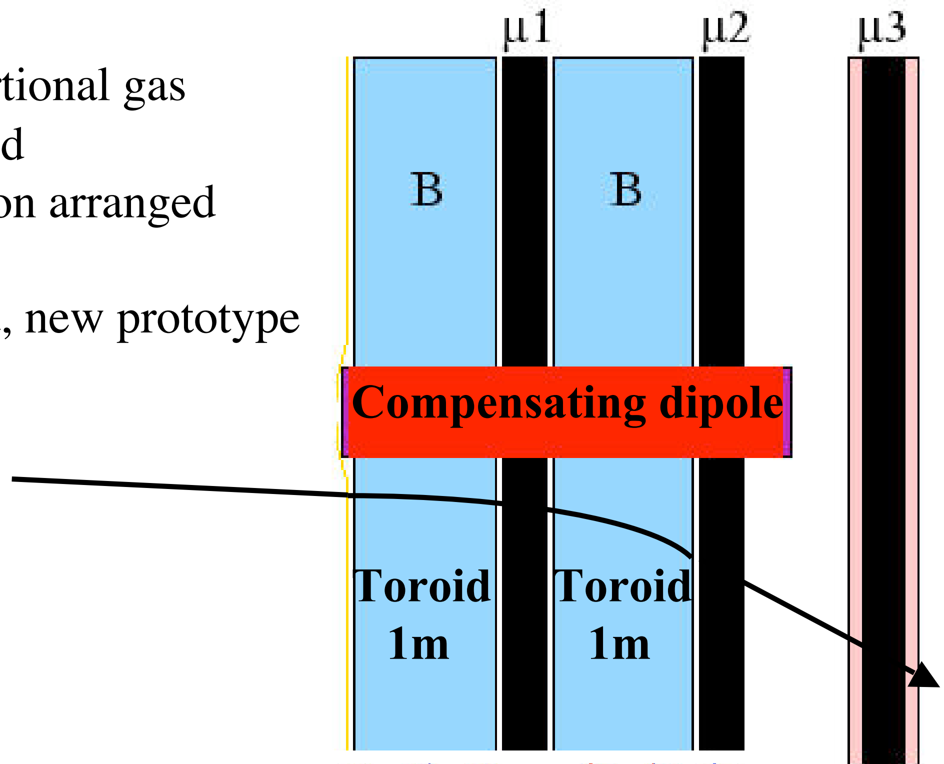
Test beam in 2004

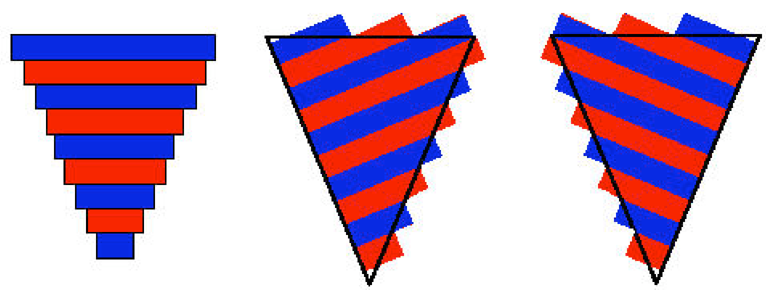


Muon Detector

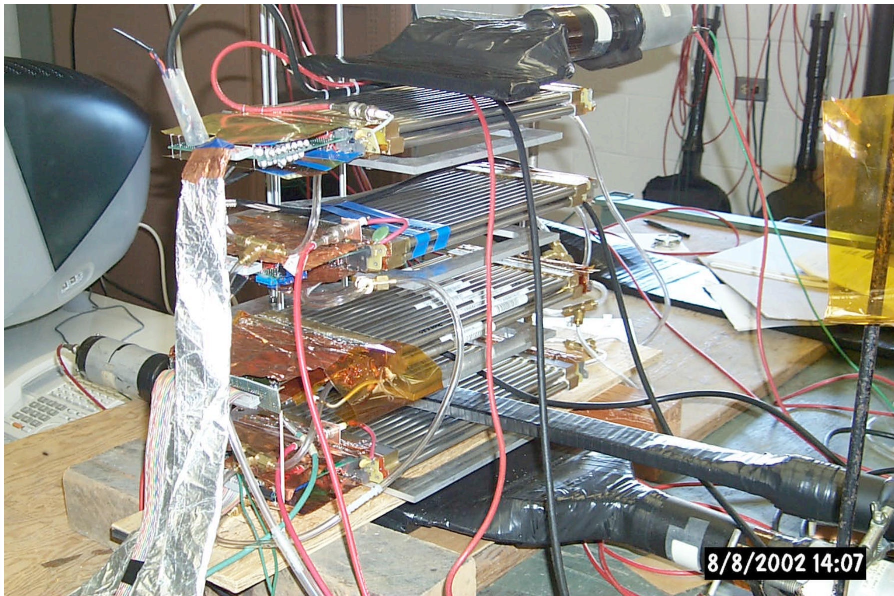
- Steel and ~1cm diameter proportional gas tubes in a toroidal magnetic field
- 3 stations with 3 views per station arranged in octants
- Tested in 1999 FNAL beam test, new prototype to be tested in 2004 beam test







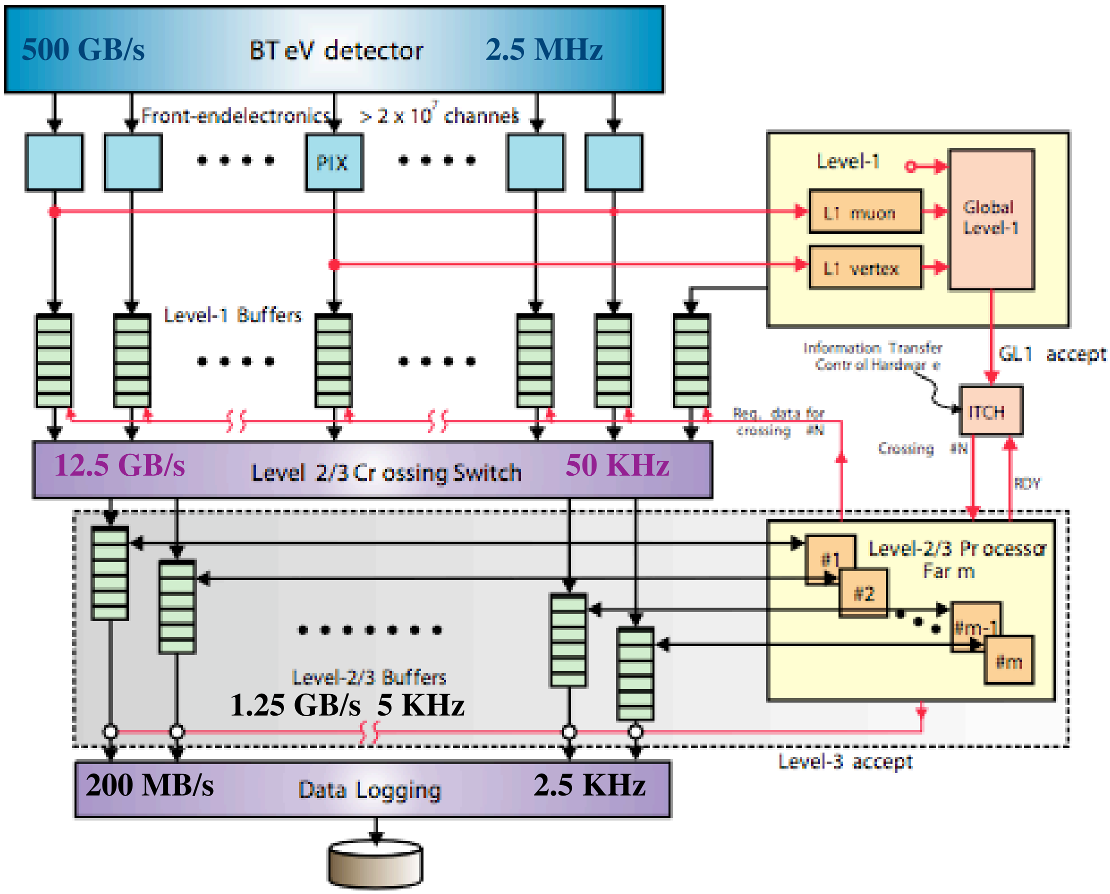
Muon Detector II



Muon prototype planks in a cosmic ray test stand at Vanderbilt

Mockup of muon detector at UIUC to understand how to install the octants in the toroid steel in the C0 Hall

BTeV Trigger



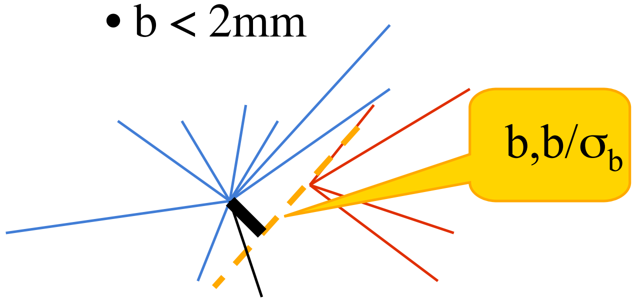
1-2 Petabytes per year

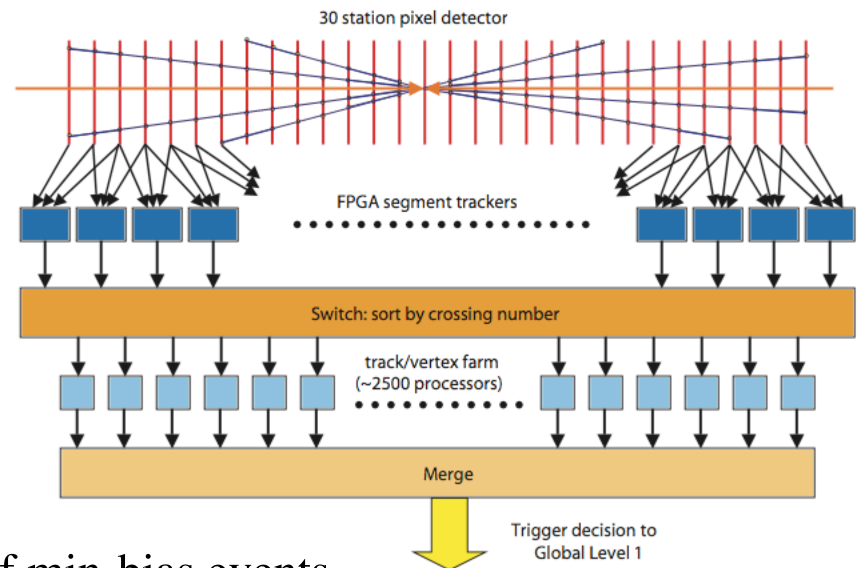
- Reconstructs primary vertex and looks for detached decays every crossing (2.5 MHz)
- Made possible by vertex detector (3D space points with excellent resolution and low occupancy)
- Pipelined and parallel processing with 1 TB of buffer
- 3 Stage Trigger
  - L1:FPGAs and DSPs
  - L2/L3: Linux PCs

BTeV L1 Pixel Trigger

Finds primary vertex and looks for
At least 2 tracks that miss it with:

- $p_T^2 > 0.25\ (\mathrm{GeV/c})^2$
- $b > 4.4\sigma_b$
- $b < 2\mathrm{mm}$





Performance with 100/1 rejection of min-bias events

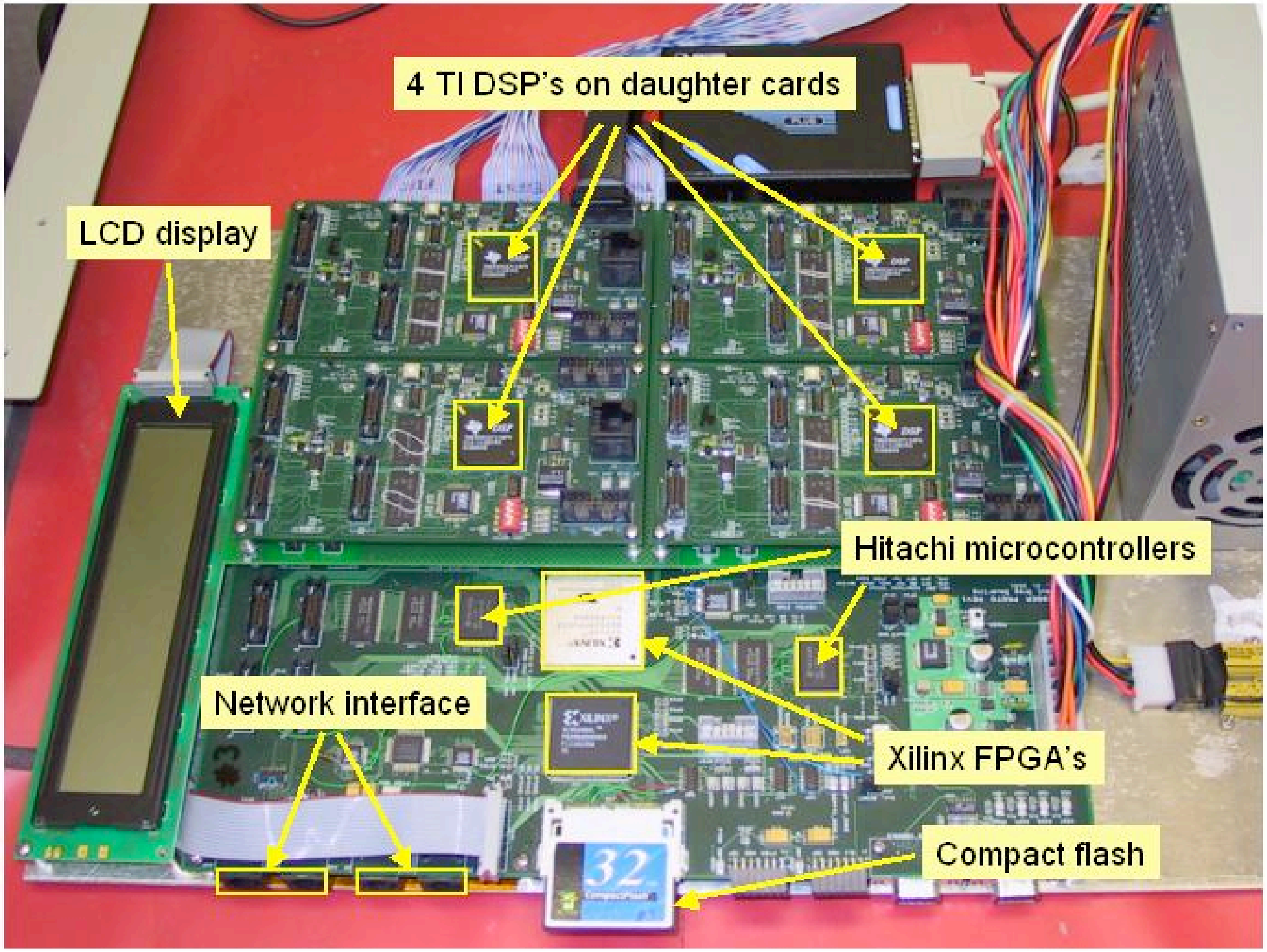
Level 1 Trigger Efficiency after selection criteria			
State	Efficiency (%)	State	Efficiency (%)
$B \to \pi^+\pi^-$	63	$B^0 \to K^+\pi^-$	63
$B_s \to D_sK$	74	$B^0 \to J/\psi\ K_s$	50
$B^- \to D^oK^-$	70	$B_s \to J/\psi K^*$	68
$B^- \to K_s\pi^-$	27	$B^0 \to K^*\gamma$	40

L1 Vertex Pixel Trigger Prototype

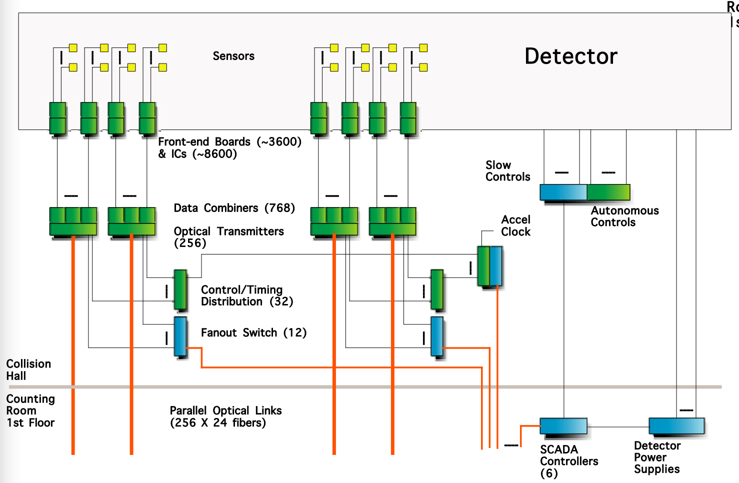
Timing tests show we are already close to the required < 350 μs L1 latency

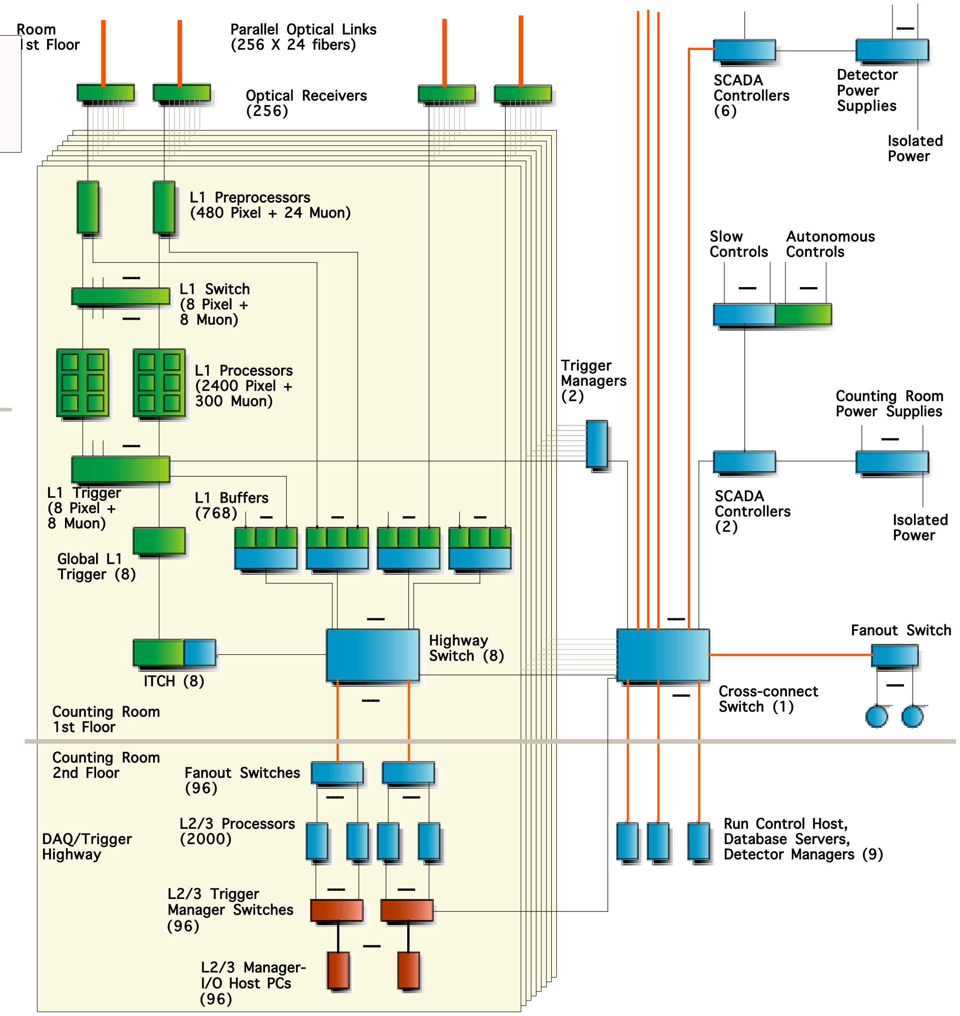
Speed is low by 2.7× w/old DSP 1.8× w/new DSP

This is without need for hand optimized assembly code!



BTeV DAQ





- Changed custom switch to a commercial one to lower risk.
- DAQ is divided into 8 “Highways”
- Output data is DST and saved on disk, i.e. full reconstruction done at Level 3

Fault Tolerance in Trigger and DAQ

- Outcome of BTeV's response to an early review on complexity of system is a research program on Real Time Embedded Systems Research (RTES)
- A collaborative effort between computer scientists and BTeV physicists funded by the NSF ($5M over five years)

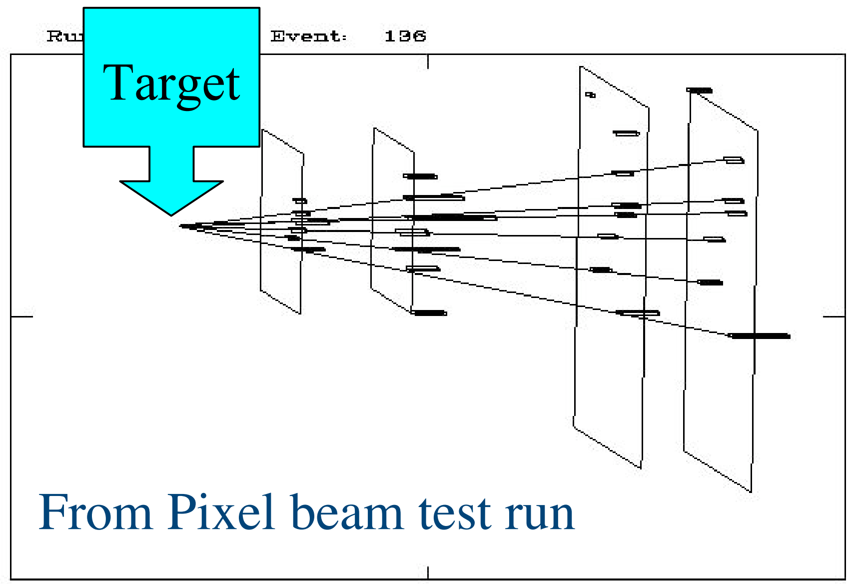
Illinois **Pittsburgh** **Syracuse** **Vanderbilt** **Fermilab** **NSF**

- Researching the design and implementation of high-performance, heterogeneous, fault-tolerant and fault-adaptive real-time systems that are embedded (*i.e.* are an integral part of the hardware they serve)
- Contains an educational outreach program where high school teachers take part in the research and develop WEB lessons for their students (Summer programs at Fermilab and Pittsburgh, integrated with QuarkNet, Link-to-Learn and College in High School programs)

Physics Simulation Tools

- Full GEANT simulations including multiple scattering, Bremsstrahlung, pair conversions, hadronic interactions and decays
- Pattern recognition is done in the trigger (for both L1 and L2)
- L3/Offline smears hits and refits tracks using "Kalman Filter"
  (no pattern recognition in L3/Offline, but do not expect large pattern recognition problems - efficient at L2 and beam test results)

Beam test with fixed-target interactions giving 10× higher track density than expected in BTeV



From Pixel beam test run

Summary I

- BTeV has an exciting physics program in CP violation and Flavour Physics

  Expect “New Physics” with extra CP violating processes

  Scenarios of “New Physics” are distinguishable in flavour sector

- Tremendous progress in detector R&D

  Still many exciting opportunities in most aspects of the design

BTeV makes excellent use of an existing DOMESTIC HEP facility in which there will have been a huge investment but doesn’t overtax precious accelerator R&D resources.

BTeV will form a key part of a world class domestic flavor physics program after the LHC takes firm possession of the energy frontier. BTeV is not just doing SM physics, it can reveal new phenomena or help explain them.

Summary II

- April 2002 PAC recommendations on updated BTeV:

  "BTeV has a broader physics reach than LHCb and should provide definitive measurements of CKM parameters and the most sensitive tests for new physics in the flavor sector"

- HEP Facilities Committee recommendations (P5 + 7):

  "These measurements [γ, α, χ] are inputs to ultimate unification, and may reveal features of hidden dimensions, for example, in the phases of couplings of supersymmetric particles. Measurements with BTeV could help distinguish among candidate models for new physics observed at the LHC."

Current Status of BTeV

- 10 Nov. 2003 - Energy Secretary Spencer Abraham announced DOE 20-year Science Facility Plan: BTeV appear as priority 12 out of 28 in "Facilities for the Future of Science: A 20-Year Outlook"

(http://www.science.doe.gov/Sub/Facilities_for_future/20-Year-Outlook-screen.pdf)

- 2 Feb. 2004 - BTeV is in President's FY 2005 budget:

(http://www.cfo.doe.gov/budget/05budget/content/science/sciencea.pdf)

Current Status of BTeV

- From the FY 2005 budget:

"In FY 2005 we will begin engineering design on a new Major Item of Equipment, the BTeV experiment at Fermilab, subject to successful independent cost and technical reviews of the project to take place in 2004." (page 74)

"The BTeV experiment will have scientific competition from a dedicated B-physics experiment at the CERN LHC, so timely completion of BTeV is important. Thus we are pursuing an aggressive schedule of R&D ($3.5M) and engineering design ($6.75 M) in FY2005 to be ready to begin fabrication in FY 2006." (page 90)

- BTeV Temple Review - March 2004

  BTeV DOE CD-1 Lehman Review - April 2004

Summary III

- If we get DOE approval and funding:

Year		2003	2004	2005	2006	2007
Tevatron Collider						BTeV
		CDF & DZero	CDF & DZero	CDF & DZero	CDF & Dzero	CDF & Dzero
Neutrino Program	B	MiniBoone	MiniBooNE	MiniB / OPEN	OPEN	OPEN
	MI			MINOS	MINOS	MINOS
Meson 120	MT	Test Beam	Test Beam	Test Beam	Test Beam	Test Beam
	MC	E907/MIPP	E907/MIPP	E907/MIPP	OPEN	OPEN

Year		2008	2009	2010	2011	2012
Tevatron Collider		BTeV	BTeV	BTeV	BTeV	BTeV
		CDF & DZero	CDF & DZero	OPEN	OPEN	OPEN
Neutrino Program	B	OPEN	OPEN	OPEN	OPEN	OPEN
	MI	MINOS	MINOS	OPEN	OPEN	OPEN
Meson 120	MT	Test Beam	Test Beam	Test Beam	Test Beam	Test Beam
	MC	E906	E906-DrellYan	E906-DrellYan	E906-DrellYan	OPEN
	ME/P	OPEN	CKM	CKM	CKM	CKM / OPEN

We are very excited about BTeV and eager to get construction funded and started!

We welcome new collaborators!

Proceed to Backup Slides

Some Reading List Suggestions

Matter/Anti-matter Asymmetry:

- Short and easy to read:
  - P. Arnold, "One Reason Why CP Violation is Way Radically Cool", 4th Workshop on Heavy Quarks, 1998, http://www.fnal.gov/projects/hq98/proceedings/arnoldp.ps.gz
  - H. Quinn, "The Asymmetry Between Matter and Antimatter", Physics Today, Feb. 2003, SLAC-PUB-9258.
- Electroweak Baryogenesis:
  - G. R. Farrar and M. E. Shaposhnikov, PRL 70 (1993) 2833; PRD 50 (1994) 774; hep-ph/9406387, 24 June 1994.
  - P. Huet and E. Sather, PRD 51 (1995) 379;
  - W. Bernreuther, hep-ph/0205279.
  - M. Berkooz, Y. Nir, T. Volansky, hep-ph/0401012.

Some Reading List Suggestions

B Physics and CP Violation:

- BTeV specific:
  - The BTeV Proposal, May 2000
  - Update to the BTeV Proposal, March 2002, BTeV-Doc-316
- B Physics:
  - B Physics at the Tevatron Run II and Beyond: FERMILAB-Pub-01/197, hep-ph/0201071
  - R. Fleischer, hep-ph/9908340
  - S. Rahatlou's talk, M. Merk's talk & J. Hewett's talk at WIN03 (http://conferences.fnal.gov/win03/WorkingGroup3.htm)

Operation at 396 ns Bunch Crossing

- BTeV was designed for $L = 2\times10^{32}$ $cm^{-2}s^{-1}$ at 132 ns i.e. $\langle 2 \rangle$ interactions/crossing
- Now expect $L \sim 2\times10^{32}$ $cm^{-2}s^{-1}$ at 396 ns, i.e. $\langle 6 \rangle$ int/crossing
  or $L \sim 1.3\times10^{32}$ $cm^{-2}s^{-1}$ at 396 ns, i.e. $\langle 4 \rangle$ int/crossing
- Verified performance by repeating many of the simulations at $\langle 4 \rangle$ and $\langle 6 \rangle$ int/crossing (without re-optimizing the code)
  Average impact across store is ~10%
- Key potential problems areas - trigger, EMCAL and RICH all hold up well based on simulations
- Ongoing work to understand fully the impact of a change to 396 ns bunch spacing, e.g. optimization of “charge collection” for pixel readout chip

Super-BaBar I

- **Problem areas**
  - **Machine:** Stu Henderson in his M2 review at Snowmass said: *“Every parameter is pushed to the limit - many accelerator physics & technology issues”*
  - **Detector:** Essentially all the BABAR subsystems would need to be replaced to withstand the particle densities & radiation load; need to run while machine fills continuously. Physics estimates are based on achieving same performance with brand new undeveloped technologies

Super-BaBar II

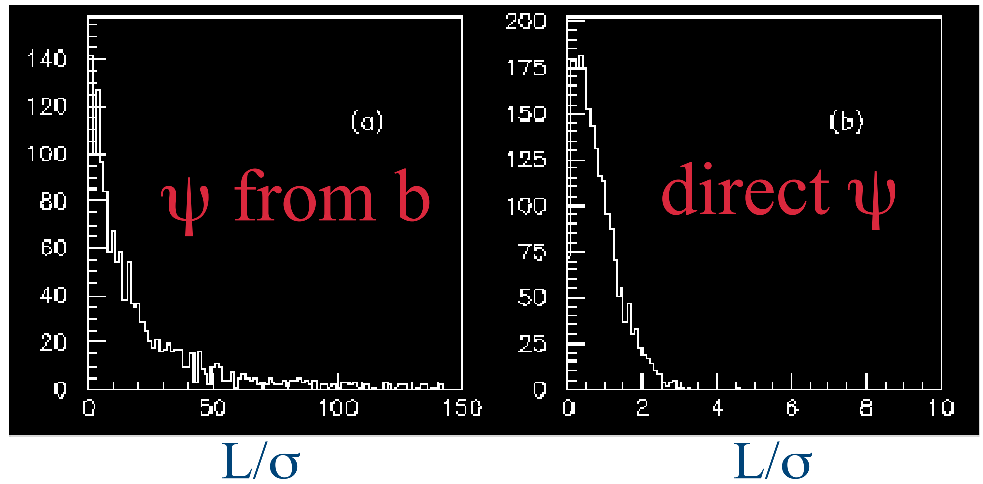
- **Examples of Detector problems *(from the E2 summary)***
  - "To maintain the vertex resolution & withstand the radiation environment, pixels with a material budget of 0.3% X_o per layer are proposed. Traditional pixel detectors which consist of a silicon pixel array bump-bonded to a readout chip are at least 1.0% X_o. To obtain less material, monolithic pixel detectors are suggested. This technology has never been used in a particle physics experiment."
  - "As a drift chamber cannot cope with the large rates & large accumulated charge, a silicon tracker has been proposed. At these low energies track resolution is dominated by multiple scattering. Silicon technology is well tested but is usually used at this energy for vertexing, not tracking. Realistic simulations need to be performed to establish if momentum resolution as good as BABAR can be achieved with the large amount of material present in a silicon tracker."
  - "There is no established crystal technology to replace the CsI(Tl)."
  - "There is no known technology for the light sensor for the SuperDIRC."

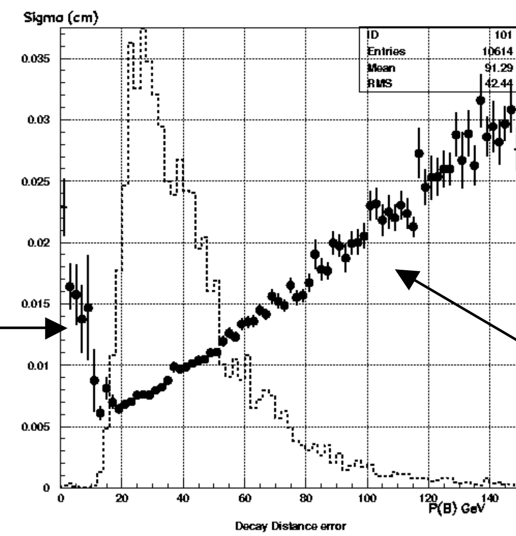
Decay Time Resolution

- Excellent decay time resolution
  - Reduces bkgd
  - Allows detached vertex trigger
- Average decay distance and the uncertainty in the average decay distance are function of the B momentum:

$\langle L \rangle = \beta\gamma c\tau_B$

$= 480\ \mu m \times p_B/m_B$





CDF/D0 region

LHCb region